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**TECHNICAL REPORT  
NATICK/TR-97/010**

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# **COMPUTER MODELING FOR INDIVIDUAL THERMAL PROTECTION**

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and  
Landa C. Hoke**

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The goal of this work is to use computer modeling to enhance individual thermal protection of clothing materials. This modeling can evaluate current clothing fabrics and also provide guidance for the development of improved materials. Calculations are performed on human skin simulant materials and also on the thermal protective fabric Nomex.<sup>R</sup> Some comparisons are made between calculated and experimental results. In addition, the computer model is used to predict the protective effects of Nomex from heat fluxes of a flash fire, a CO<sub>2</sub> laser or a nuclear explosion. The model also is used to evaluate the importance of several material parameters (density, specific heat capacity, thermal conductivity) in the thermal protection by Nomex. Finally, the thermal computer code is used to facilitate experimental work pertaining to protection from thermal effects of nuclear weapons by making correlations between nuclear pulses and trapezoidal pulses (which can be obtained in the laboratory).

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# COMPUTER MODELING FOR INDIVIDUAL THERMAL PROTECTION

## I. INTRODUCTION

The purpose of this work is to improve individual thermal protection by predicting thermal responses of materials using computer modeling. This modeling evaluates the current protective capabilities of clothing material, simulates new materials and examines their protective capabilities, and provides information that can facilitate experimental work concerning thermal protection from nuclear weapons.

The model that was used for this work is currently being developed at Natick Research, Development and Engineering Center (NRDEC) and at Northeastern University (1). The code consists of a thermal energy transport procedure and optical thermal effects procedure. The thermal transport portion of the code was used here.

The thermal responses of a skin simulant and Nomex<sup>R</sup> are investigated here. These materials are modeled separately in one-layer calculations. Also, the thermal responses of both materials are evaluated simultaneously by performing two-layer calculations. The two-layer calculations predict skin simulant temperature profiles when the simulant is protected thermally by Nomex. This is a simulation of Nomex clothing being worn by an individual in a thermally hazardous environment.

For single-layer Nomex calculations and also for two-layer (simulant and Nomex) calculations, comparisons are made between temperatures predicted by the model and experimentally measured temperatures in the laboratory.

The thermal computer model is used to predict the protective effects afforded by Nomex. Temperature profiles are calculated for the skin simulant material with and without Nomex protection when exposed to heat fluxes appropriate to a flash fire, CO<sub>2</sub> laser irradiation, or a nuclear explosion.

In addition, in simulations of thermal protection of various Nomex materials, the effects of density, heat capacity, and thermal conductivity of Nomex are examined. In order to model a new material, values of material parameters are changed from their values for the actual Nomex material. The effect of these changes in material parameters on thermal protection is evaluated by comparing the temperature profile (temperature as a function of time) of the skin simulant protected by the various simulated Nomex materials to the temperature profiles of the skin simulant protected by actual Nomex material.

The computer model is also used to facilitate work pertaining to individual protection from thermal effects of nuclear weapons. Nuclear-shaped pulses cannot be obtained in this laboratory. However, trapezoidal pulses are experimentally possible. The model is used to determine the value of trapezoidal pulse parameters that correlate with a specified nuclear pulse so that the effect of nuclear pulses can be evaluated in the laboratory.



## II. THERMAL COMPUTER MODELING

### A. Modeling Procedure

The thermal code was run on Natick's HP-877 mainframe computer. Three sequential computer submissions are required in order to run the code. These are the preprocessing procedure, the main program procedure, and the postprocessing procedure. User input to the code is accomplished by editing two files (preprocessor and postprocessor files). Additional information concerning input, output, and code usage is provided below.

The preprocessor file provides input information specific to each individual case. Examples of the preprocessor file for one- and two-layer calculations are shown in Appendix A. Explanations for the parameters included in this file are provided in reference (1). Several additional lines have been added to this file which are not discussed in reference (1). These additional lines allow specification of a one-layer versus a multilayer problem and have been part of the code modification by one of the authors (BSD) that was accomplished during this current work. A nontrivial aspect of this work was to determine values for input parameters for the preprocessor file. (This aspect of the modeling procedure for several of the input parameters is discussed in detail in Section 2.2. of this report.) After the preprocessor file is specified and the preprocessor procedure completed, then the main program can be run. (Running the main program is the procedure which requires a large amount of CPU time on the HP and which results in long turnaround times.)

After the main program is run, the postprocessing procedure is initiated. The postprocessor file specifies the depth in the material sample for which a temperature profile is to be calculated. It was necessary to modify the postprocessor file input procedure to accomplish this current work so that two-layer calculations could be performed. Examples of the postprocessor file are shown in Appendix A. Additional documentation, which is helpful for both preprocessor and postprocessor use, is provided in reference (2).

Output of the code consists of a computer file which contains specified times after the initiation of laser irradiation and the corresponding calculated temperature values at the specified depth in the material sample. This output file is downloaded from the HP to the hard disc of a PC and then accessed for data analyses using the graphics software Quattro Pro. Plots are constructed of times after laser irradiation versus corresponding temperatures at the thermistor location in the irradiated material.

### B. Input to the Code

Input parameters to the computer program include the density,  $\rho$ , the heat capacity,  $C_p$ , and the thermal conductivity,  $k$ , and also the physical dimensions (height, length, width) of the material sample. It is also necessary to specify the minimum number of nodes required in order to achieve reasonable temperature predictions. Other input includes the length of the laser pulse, the pulse shape, and the run time. In addition, the thermistor location for the material needs to be specified.

## 1. Material Parameters ( $\rho$ , $C_p$ , $k$ )

An initial aspect of this project was to determine values for three material parameters ( $\rho$ ,  $C_p$ , and  $k$ ) for each of the two materials (skin simulant and Nomex).

### a. Skin Simulant Material

Predicting the thermal responses of a human skin simulant under different conditions can facilitate the understanding of the response of human skin to different thermal insults and is important information in evaluating thermal hazards. In addition, since a skin simulant material is used in laboratory experiments instead of human skin, using the computer model to predict thermal responses of simulant material provides a means to make comparisons between calculated and experimental results.

One criterion for a skin simulant material that allows its thermal behavior to be correlated with the thermal behavior of human skin is that the mathematical product of the three parameters  $\rho \times C_p \times k$  (or thermal inertia) be as close a match to this product for human skin as possible. Torvi (3) provides values of these parameters for human epidermis and human dermis. For human epidermis the density is  $1200 \text{ kg/m}^3$  and the heat capacity is  $3598 \text{ J/(kg-K)}$  and a value for the thermal conductivity is  $0.255 \text{ W/(m-K)}$ . For human dermis the density is  $1200 \text{ kg/m}^3$  and the heat capacity is  $3222 \text{ J/(kg-K)}$  and a value for the thermal conductivity is  $0.523 \text{ W/(m-K)}$ . The mathematical product of these parameters for human epidermis is 1.10 and for human dermis this product is 2.02.

### Molded Discs

Initially, an attempt was made to measure the three properties for the skin simulant material here at Natick. This material is urea-formaldehyde/silica (60/40). The material is molded into hard cylindrical discs approximately a centimeter in height and two and one-half centimeters in diameter for laboratory use.

### Density ( $\rho$ )

Five discs were selected for density measurements. The mass of these discs was measured in the laboratory and the volume of each disc was calculated based on measurements of the height and diameter. Using this information, the density of each disc was calculated. A range of values for these five discs was determined to be from  $1.209 \text{ g/cm}^3$  to  $1.275 \text{ g/cm}^3$  with an average value of  $1.249 \text{ g/cm}^3$ . Thermogravimetric analysis (TGA) of a sample of the urea formaldehyde/silica powder used to produce the discs revealed that this powder was approximately 60% urea-formaldehyde and 40% silica by weight. Therefore, the variation in densities of the molded discs suggests that some aspect of the molding process may have caused some variations in the compositions of the final discs.

### Heat Capacity ( $C_p$ )

The heat capacity was measured with Natick's differential scanning calorimetry (DSC) apparatus. Two of the five discs chosen at random were broken into smaller pieces by the machine shop to facilitate the laboratory analyses. Data from the material from these two discs for the temperature range 20°C to 50°C provides a range of  $C_p$  values for four DSC runs for comparison and is shown in Table 1. (page 9). These measurements provide a variation in  $C_p$  values for the samples evaluated. Some of the variations may have resulted from the DSC measurement process itself. (Inconsistencies of DSC sample sizes may have been a contributing factor to these variations.) Further laboratory analyses, not conducted for this current work, are required to identify the cause of the variations.

### Thermal Conductivity ( $k$ )

There was no experimental apparatus at Natick to determine a value for  $k$  and there was not sufficient available information to calculate a value for  $k$ .

### Approximations for $\rho$ , $C_p$ , and $k$

Based on the above information, it was not possible to determine the three parameters for the skin simulant material by performing laboratory analyses of this material here at Natick. However, an approximation for these parameters for the skin simulant discs was required in order to proceed with computer modeling.

References by Maggio (4) and Derksen et al. (5) provided guidance to this laboratory for the composition by weight of the two components of the discs (urea-formaldehyde/silica (60/40)), and also for the time, temperature, and pressure requirements to mold the urea-formaldehyde/silica powder into the hard skin simulant discs. Since these two references were used as guidance for making the skin simulant discs, information obtained from these references concerning the three material parameters ( $\rho$ ,  $C_p$ ,  $k$ ) provided a reasonable approximation for values to use in the thermal computer model. Maggio's paper reports a density of 1.82 g/cm<sup>3</sup>. (This is somewhat higher than the density measurements on the molded skin simulant discs.) Derksen et al. report a  $k$  value of  $13.1 \times 10^{-4}$  (cgs units). This same reference reports the mathematical product of  $\rho \times C_p$  as 0.65 (cgs units). Therefore, Maggio's reported density of 1.82 g/cm<sup>3</sup> and the Derksen et al. value for  $\rho \times C_p$  can be used to deduce a value for  $C_p$ . This  $C_p$  value is 0.36 (cgs units). The three material parameters in SI units are 1820 kg/m<sup>3</sup> for the density, 1507 J/(Kg-K) for the specific heat capacity, and 0.5484 W/(m-K) for the thermal conductivity. The product of these parameters is 1.50, which falls between the corresponding values for this mathematical product for human epidermis and human dermis.

### Nomex

The Nomex material used to collect experimental data is MIL-C-44077. This material is 95/5 Nomex/Kevlar and is 4.5 oz/yd<sup>2</sup>. Values for the three material parameters were not readily available for this specific material. However, values for these parameters were available for another similar Nomex material ARAMID Type 430 from information provided by Du Pont in MULTIFIBER Bulletin X-272 (6). Therefore, values for the material parameters for Nomex ARAMID Type 430 were used as a reasonable approximation for values for these parameters for MIL-C-44077. Inputs used for the computer model are for the density 1.38 kg/m<sup>3</sup>, the specific heat (25°C) 1213 J/(kg-K), and the thermal conductivity 0.13 W/(m-K).

## 2. Material Dimensions and Thermistor Location

Figures 1(a). - 1(c). show the actual physical dimensions of the materials and also the computer input specification used for these calculations and will be helpful for the following discussion.

### a. Skin Simulant Material

The goal when making the skin simulant discs was to locate the thermistor at a depth representative of the epidermis/dermis interface in human skin. (Note, however, that there is considerable variation in human skin.) The reason this depth was chosen is that temperatures at this location have been correlated with skin burn. (Calculated temperatures at the thermistor location can be compared to experimental data when it is available.) This was the location of interest both when the skin simulant material was examined alone and also when experiments were conducted with the Nomex material protecting the skin simulant disc (two layers).

The thermistor depth in the skin simulant discs is 0.0001 m. A small slab of material was used as a reasonable geometry for input to the calculations. (This is the same geometry used earlier when performing calculations in association with Professor Kowalski.) The thickness of this slab was 0.002 meter and the other two dimensions were each 0.01 meters. This rectangular slab of material specified for the calculations constitutes only a small part of the actual volume of the cylindrical disc used for laboratory experiments. The back surface temperatures of the skin simulant slab were of interest in order to ensure the reasonableness of using a semi-infinite approximation. (This is important as a calibration procedure to insure that temperature predictions are reliable.)

### b. Nomex

In experiments involving only the single material Nomex, the thermistor was located at the back surface of the material. Therefore, for the single layer Nomex calculations, the back surface of the material was specified in the postprocessor file as the location to calculate temperature profiles.

The thickness of the Nomex fabric used in the laboratory experiments was measured to be 0.0005 m. The other two dimensions were each specified to be 0.01 meters, the same as for the simulant material.

## 3. Run Time, Pulse Time, and Pulse Shape

For all calculations except those pertaining to nuclear weapons, a square pulse was specified. The computer simulated run time for these calculations was two seconds and the pulse length was one second. Laser irradiation starts at zero seconds and stops at one second. Therefore, the thermal response of the material(s) is evaluated for two seconds (one second during laser irradiation and one second after laser irradiation has ceased).

In order to obtain experimental information in this laboratory pertaining to nuclear weapons protection, a correlation must be made between a nuclear shaped pulse (not achievable in this laboratory) and a trapezoidal pulse (achievable in this laboratory). For these nuclear weapons calculations, nuclear and trapezoidal pulses are specified as input to the program (versus a square pulse).

Both of the ramp times (up and down) for all trapezoidal pulses were specified to be 0.1 seconds (total ramp time 0.2 seconds). See Figure 2. The plateau time is a parameter that can be varied for each different trapezoidal pulse. The total pulse time (total ramp time (0.2 s) plus plateau time) for each of the trapezoidal pulses could therefore be different also. For nuclear pulses, the pulse time was a function of the yield (7).

A simulated run time of five seconds was specified for both nuclear and trapezoidal pulses (versus two seconds for the square pulse).



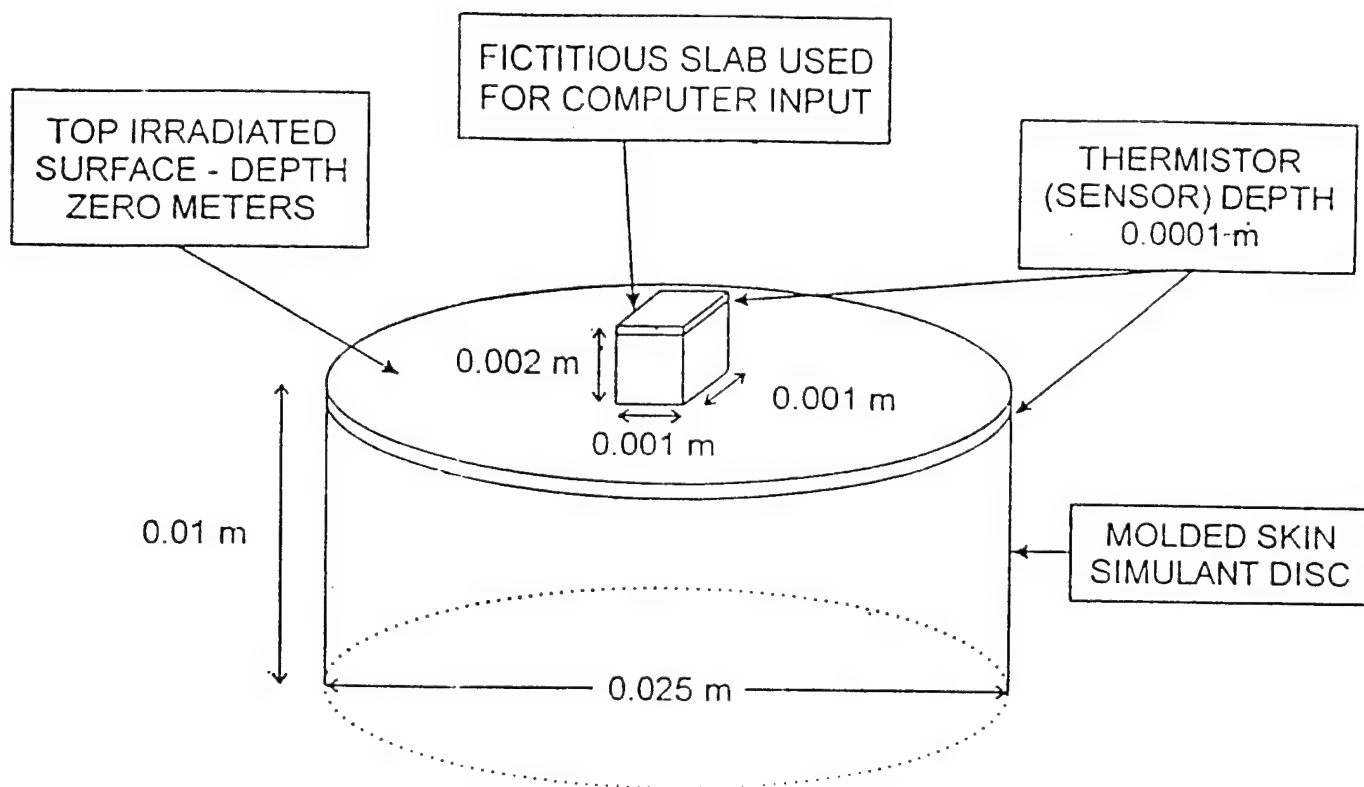


FIGURE 1(a). SKIN SIMULANT MATERIAL GEOMETRY AND COMPUTER INPUT - ONE LAYER

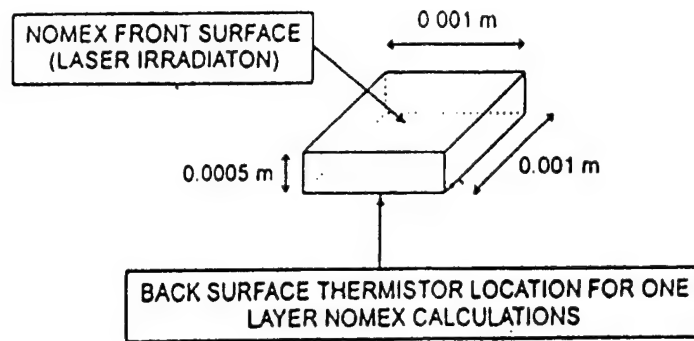


FIGURE 1(b). NOMEX COMPUTER INPUT FOR ONE LAYER

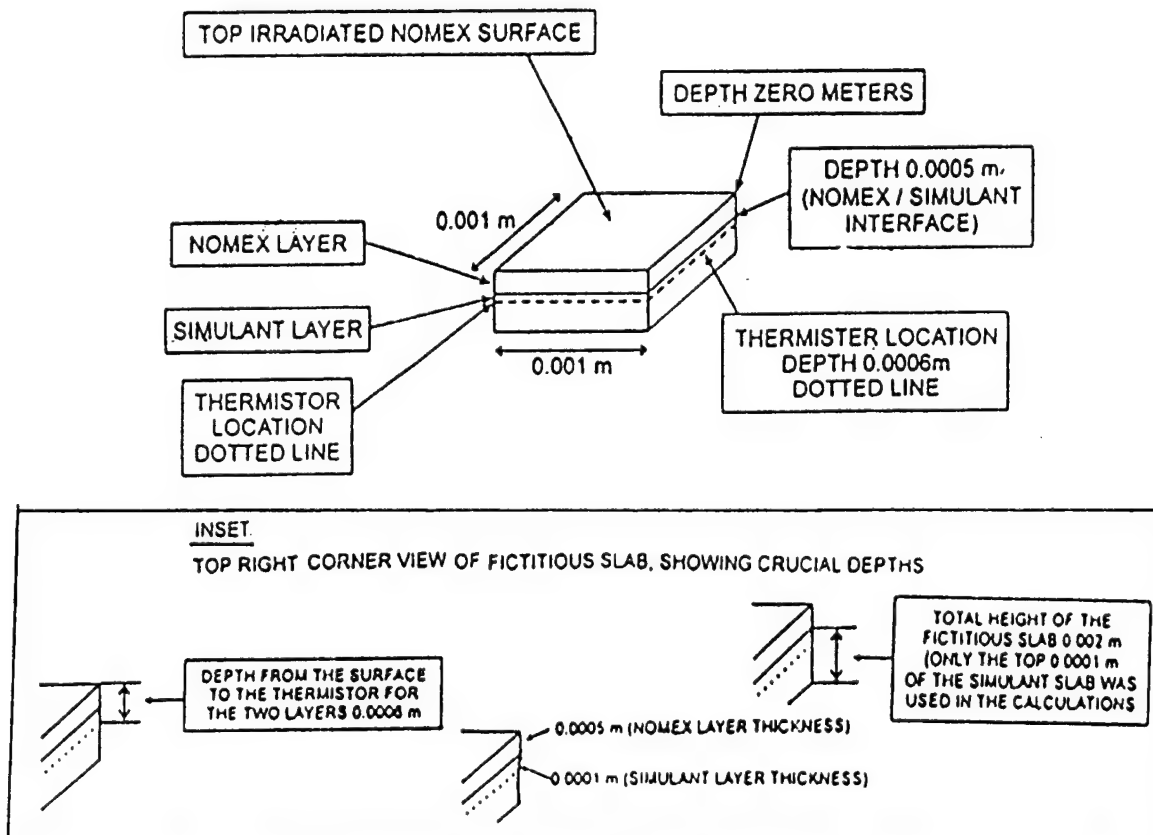


FIGURE 1(c). SKIN SIMULANT AND NOMEX COMPUTER INPUT--TWO LAYERS

TABLE 1. DSC-MEASURED  $C_p$  VALUES FOR SKIN SIMULANT

RUN (NUMBER)	RANGE OF MEASURED $C_p$ VALUES CAL/(g · °C)
1	0.3702 - 0.6477
2	0.2828 - 0.4200
3	0.0223 - 0.3903
4	0.0100 - 0.0195

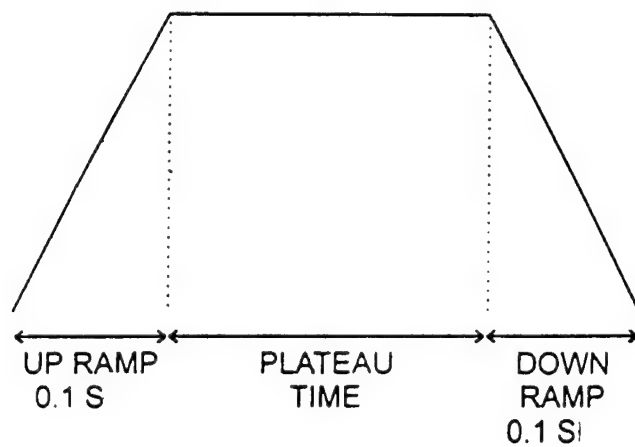


FIGURE 2. TRAPEZOIDAL PULSE

### III. MODELING SKIN SIMULANT MATERIAL - ONE LAYER

The sensors being modeled are of sufficient thickness to be considered as semi-infinite solids. Such a solid would show no rear-surface temperature rise after irradiation of the front surface. An important step in setting up the model is to determine the minimum number of nodes required to simulate a semi-infinite material. It is important to use the minimum number of nodes in order to reduce the computer time required for calculations (for example, a typical two-layer case with a simulated run-time of two seconds might have a two-hour turnaround time from program input through postprocessing).

The method is to start with a small number of nodes and then increase the number of nodes until no (within a reasonable tolerance) rear-surface temperature increase is predicted. A 60-node configuration provided a satisfactory rear-surface temperature profile from the time of initial laser irradiation, continuing through a two-second time period. Therefore, 60 nodes were chosen for the subsequent modeling runs.

The time versus temperature graph for the skin simulant material at a flux of  $83.72 \times 10^4 \text{ W/m}^2$  is shown in Figure 3. This figure shows the temperature profiles of the front surface of the material, the thermistor (sensor) depth, and the back surface. The material response to the one-second laser pulse is clearly evident in the temperature profiles for the front surface and thermistor locations. There is a rise in temperature in response to the incident heat flux from the laser. After one second when the heat source is turned off, the material temperature starts to decrease. The flat temperature profile required for validation of the semi-infinite approximation is evident for the back surface.



## IV. MODELING NOMEX - ONE LAYER

### A. Minimum Number of Nodes

In a similar manner as for the skin simulant material, before results can be obtained for the Nomex material, it is necessary to determine the minimum number of nodes required in order to make reasonable temperature predictions. Calculations were performed starting with a small number of nodes and then increasing the number of nodes until the temperature profile, which was predicted at the back surface of the fabric (thermistor location), did not show a significant change if the number of nodes was increased further. Temperature profiles were calculated for 5, 10, 20, 40, and 80 nodes. Based on this information, the minimum number of nodes selected in order to make temperature predictions for the response of the Nomex material at  $19.4 \times 10^4 \text{ W/m}^2$  was determined to be 20.

### B. Results

Four calculations were performed for four different fluxes. These correspond to six different data sets (two experiments were performed twice at the same flux). Numerical values for calculated and experimental results are shown in Tables 4(a). and 4(b). These results are shown graphically in Figures 4(a). - 4(d). Figures 4(a). and 4(c). each show two different sets of experimental data at the same flux. These figures show that there is considerable variation in the experimental data. Considering the approximations made for the input parameters and also the experimental variations, the comparisons between the experimental and the calculated values are reasonable.

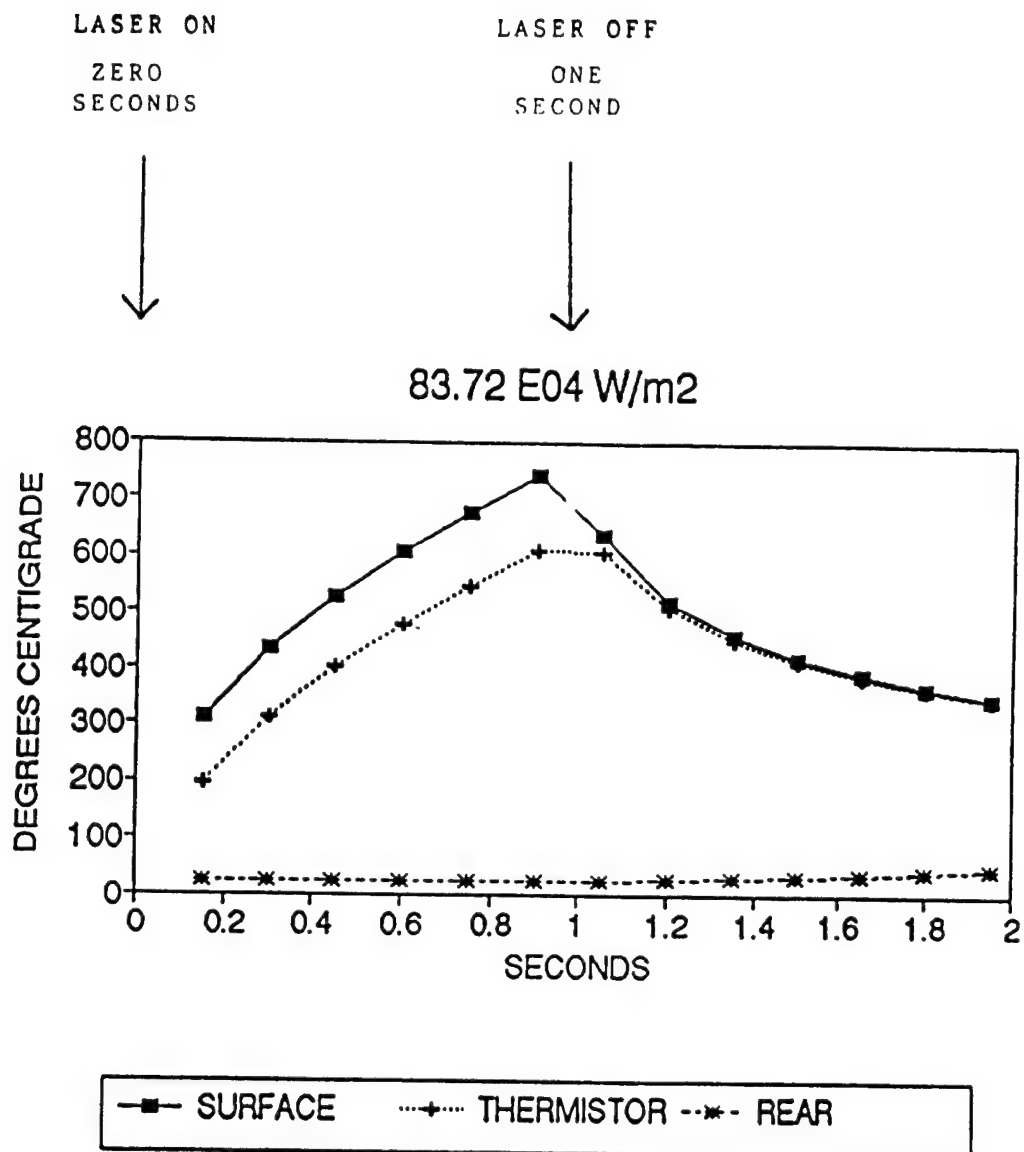


Figure 3      Predicted Skin Simulant Response  
                     to CO<sub>2</sub> Laser

TABLE 2(a). Experimental Results for Nomex  
for One Layer

S	DEGREES CENTIGRADE (19.4 W/m2 X 10+4)	(19.4 W/m2 X 10+4)	(21.1 W/m2 X 10+4)	(13.6 W/m2 X 10+4)	(13.6 W/m2 X 10+4)	(13.1 W/m2 X 10+4)
0.15						
0.30	51.20	58.18	39.09	46.78	41.60	43.56
0.45						
0.60	50.52	65.51	74.06	69.51	52.73	62.86
0.75						
0.90	82.72	154.92	106.83	73.49	74.12	78.22
1.05						
1.20	108.28	189.44	155.40	103.38	82.78	77.14
1.35						
1.50	117.83	192.00	191.42	116.28	89.89	77.14
1.65						
1.80	112.68	168.80	172.98	146.48	89.46	82.32
1.95						

TABLE 2(b). Calculated Results for Nomex  
for One Layer

S	DEGREES CENTIGRADE (19.4 W/m2 X 10+4)	(19.4 W/m2 X 10+4)	(21.1 W/m2 X 10+4)	(13.6 W/m2 X 10+4)	(13.6 W/m2 X 10+4)	(13.1 W/m2 X 10+4)
0.15	24.35	24.35	24.37	24.31	24.31	24.30
0.30	28.82	28.82	29.22	27.44	27.44	27.32
0.45	42.15	42.15	43.72	36.78	36.78	36.32
0.60	62.88	62.88	66.27	51.32	51.32	50.32
0.75	88.59	88.59	94.23	69.34	69.34	67.68
0.90	117.47	117.47	125.64	89.58	89.58	87.18
1.05	148.35	148.35	159.23	111.23	111.23	108.03
1.20	179.72	179.72	193.35	133.22	133.22	129.22
1.35	205.35	205.35	221.22	151.19	151.19	146.52
1.50	222.68	222.68	240.07	163.34	163.34	158.23
1.65	233.73	233.73	252.09	171.09	171.09	165.69
1.80	240.64	240.64	259.61	175.93	175.93	170.35
1.95	244.91	244.91	264.25	178.93	178.93	173.24



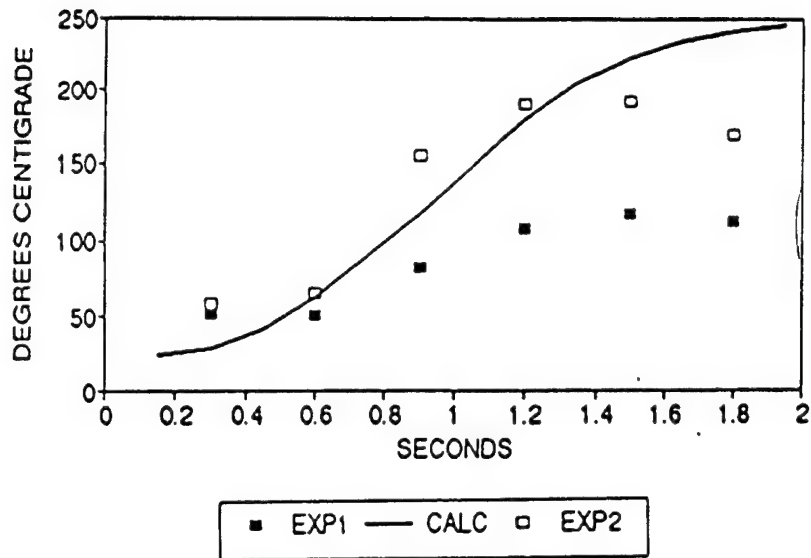


Figure 4 (a). Nomex -  $13.6 \times 10^4 \text{ W/m}^2$ .

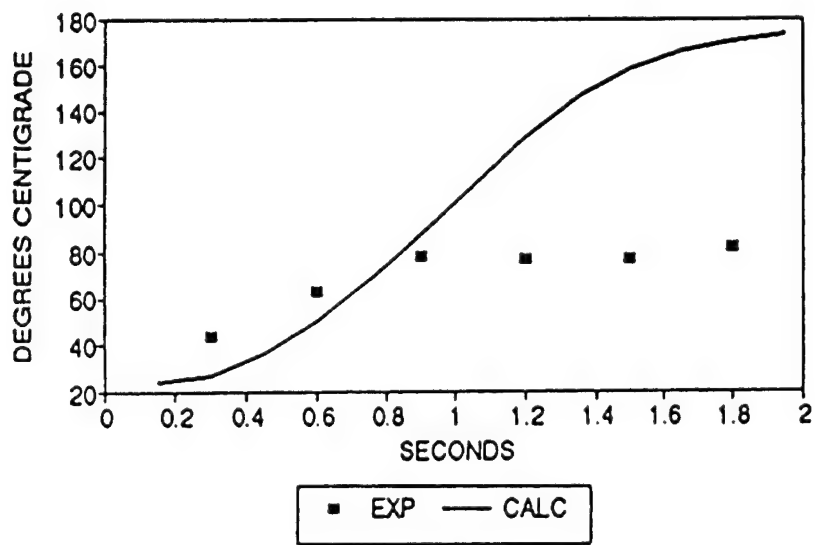


Figure 4 (b). Nomex -  $21.1 \times 10^4 \text{ W/m}^2$ .

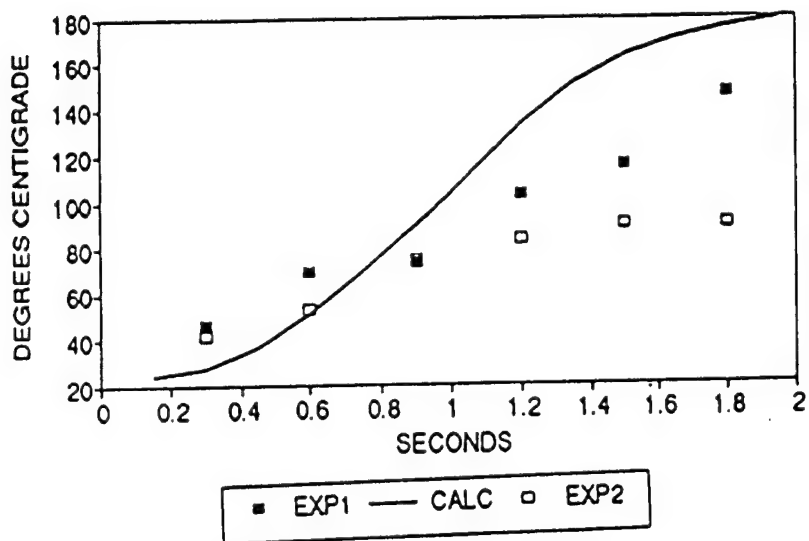


Figure 4 (c). Nomex -  $19.4 \times 10^4 \text{ W/m}^2$

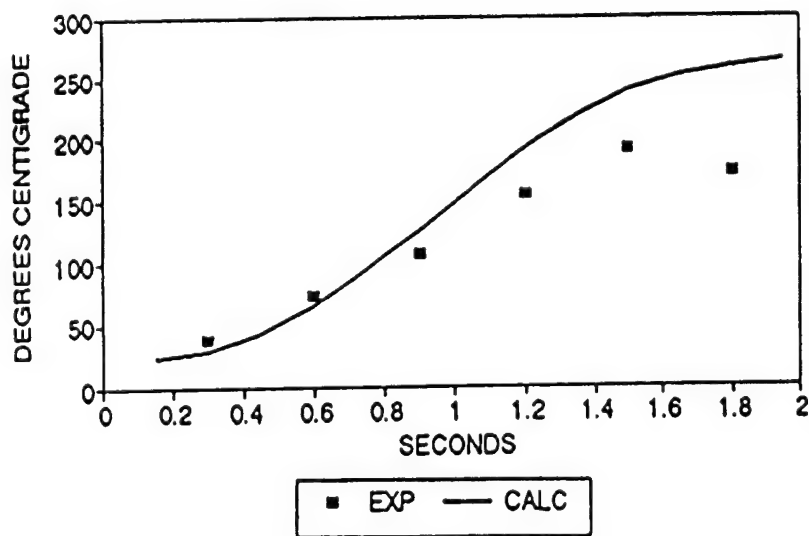


Figure 4 (d). Nomex -  $13.1 \times 10^4 \text{ W/m}^2$

TABLE 3 (a). Simulant Protected by Nomex -  
Experimental Results

S.	DEGREES CENTIGRADE (23.4 W/m <sup>2</sup> X 10 <sup>4</sup> )	(21.2 W/m <sup>2</sup> X 10 <sup>4</sup> )	(23.1 W/m <sup>2</sup> X 10 <sup>4</sup> )	(14.9 W/m <sup>2</sup> X 10 <sup>4</sup> )	(15.8 W/m <sup>2</sup> X 10 <sup>4</sup> )	(15.4 W/m <sup>2</sup> X 10 <sup>4</sup> )
0.15						
0.30	30.28	36.25	38.07	37.74	39.27	39.91
0.45						
0.60	37.53	42.28	43.11	40.92	42.76	42.75
0.75						
0.90	45.12	49.78	49.67	47.08	48.49	48.22
1.05						
1.20	49.53	53.76	53.93	51.25	52.65	52.07
1.35						
1.50	55.24	57.96	58.94	53.48	55.09	54.34
1.65						
1.80	59.26	60.89	62.64	54.78	56.90	55.81
1.95						

TABLE 3 (b). Simulant Protected by Nomex -  
Calculated Results

S	DEGREES CENTIGRADE (23.4 W/m <sup>2</sup> X 10 <sup>4</sup> )	(21.2 W/m <sup>2</sup> X 10 <sup>4</sup> )	(23.1 W/m <sup>2</sup> X 10 <sup>4</sup> )	(14.9 W/m <sup>2</sup> X 10 <sup>4</sup> )	(15.8 W/m <sup>2</sup> X 10 <sup>4</sup> )	(15.4 W/m <sup>2</sup> X 10 <sup>4</sup> )
0.15	24.22	24.22	24.22	24.21	24.21	24.21
0.30	24.89	24.82	24.88	24.64	24.66	24.65
0.45	27.45	27.14	27.40	26.27	26.39	26.34
0.60	32.04	31.31	31.94	29.19	29.50	29.36
0.75	38.27	36.94	38.08	33.16	33.70	33.46
0.90	45.66	43.65	45.39	37.87	38.69	38.33
1.05	53.89	51.09	53.51	43.10	44.24	43.74
1.20	62.58	58.97	62.09	48.64	50.12	49.46
1.35	70.54	66.18	69.95	53.71	55.49	54.70
1.50	76.69	71.75	76.01	57.62	59.64	58.74
1.65	81.05	75.70	80.32	60.40	62.58	61.61
1.80	84.01	78.39	83.24	62.28	64.58	63.56
1.95	85.94	80.14	85.15	63.51	65.89	64.83

## **V. MODELING SKIN SIMULANT AND NOMEX SIMULTANEOUSLY - TWO LAYERS**

In order to simulate a Nomex material being worn in a thermally hazardous environment, calculations and experiments were performed involving both the simulant and the Nomex at the same time. In these experiments, the Nomex is placed on top of the skin simulant disc in order to cover it and protect it from the CO<sub>2</sub> laser irradiation. The two-material Nomex/simulant combination is irradiated and the temperatures at the thermistor (embedded 0.0001 m in the simulant disc or 0.0006 m from the outer (front) surface of the Nomex) are determined.

### **A. Minimum Number of Nodes for Nomex and Simulant**

The number of nodes required for each layer in the two layer calculation was evaluated.

Assigning the number of nodes for Nomex to be 10, results from 60, 70, and 80 simulant nodes were examined. Based on this information, 60 nodes were selected for the simulant layer for two-layer calculations.

For all the two-layer calculations performed for this work, 10 nodes were specified for the Nomex layer and 60 nodes for the simulant layer.

### **B. Results**

Six different data sets were collected in the laboratory using a CO<sub>2</sub> laser with Nomex protecting the simulant from the laser irradiation. Three data sets had fluxes at approximately 22 W/m<sup>2</sup> and the other three data sets had smaller fluxes at approximately 15 W/m<sup>2</sup>. The thermal code was used to predict the temperatures at each of these fluxes at the thermistor location. These results are provided in Tables 3(a), and 3(b). The results are shown graphically in Figures 5(a). - 5 (f).

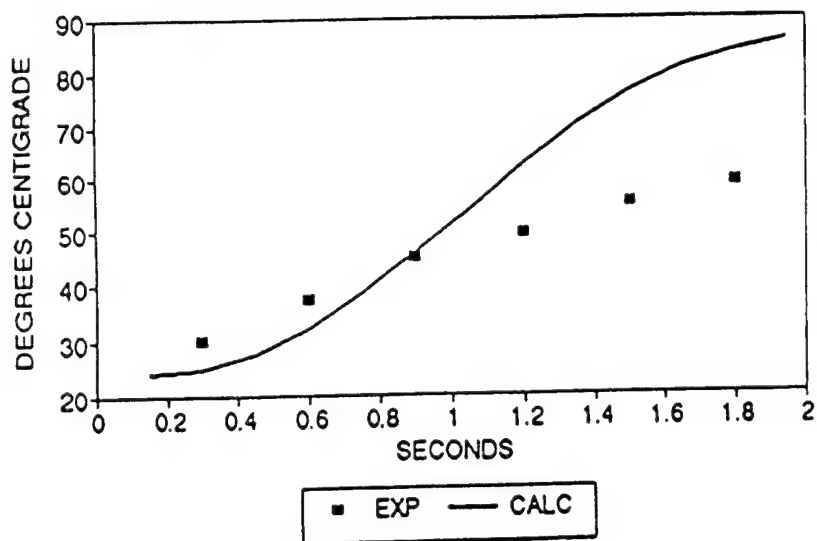


Figure 5 (a). Simulant Protected by Nomex -  
 $23.4 \times 10^4 \text{ W/m}^2$ .

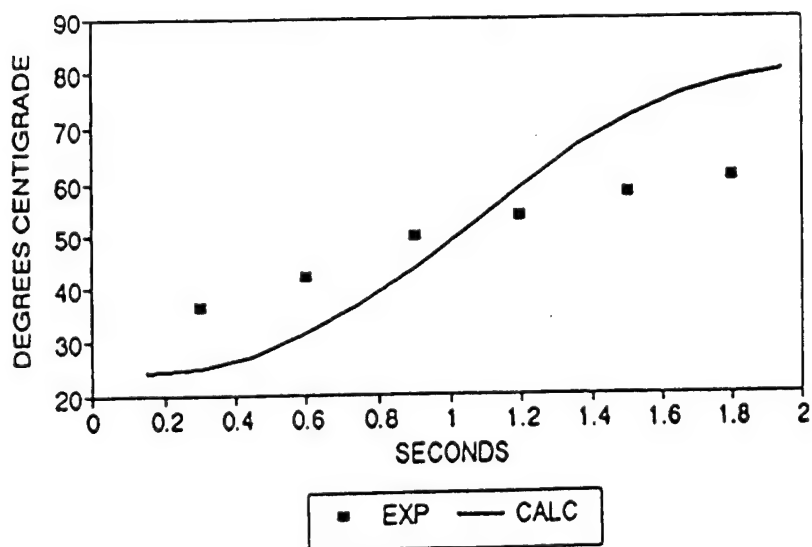


Figure 5 (b). Simulant Protected by Nomex -  
 $21.2 \times 10^4 \text{ W/m}^2$ .

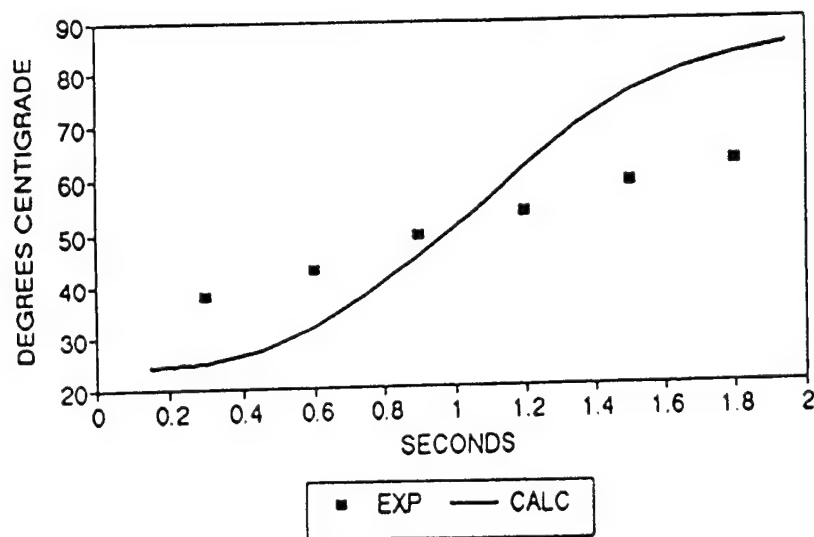


Figure 5 (c). Simulant Protected by Nomex -  
 $23.1 \times 10^4 \text{ W/m}^2$ .

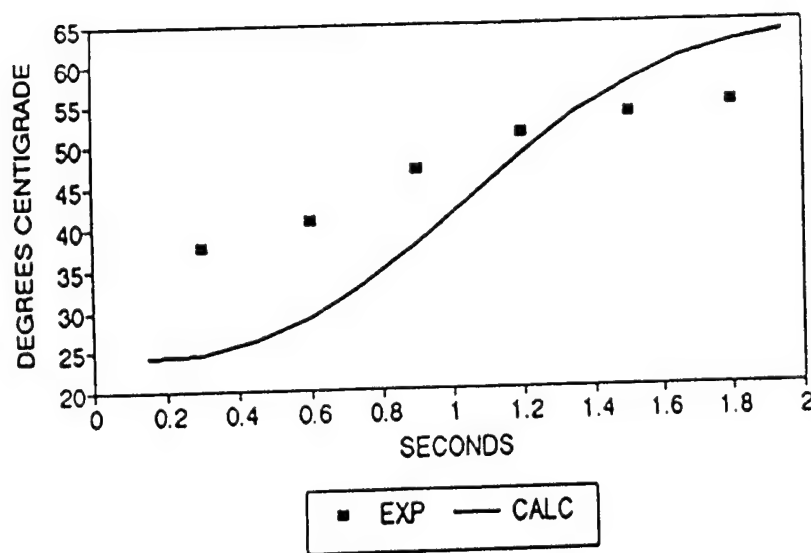


Figure 5 (d). Simulant Protected by Nomex -  
 $14.9 \times 10^4 \text{ W/m}^2$ .

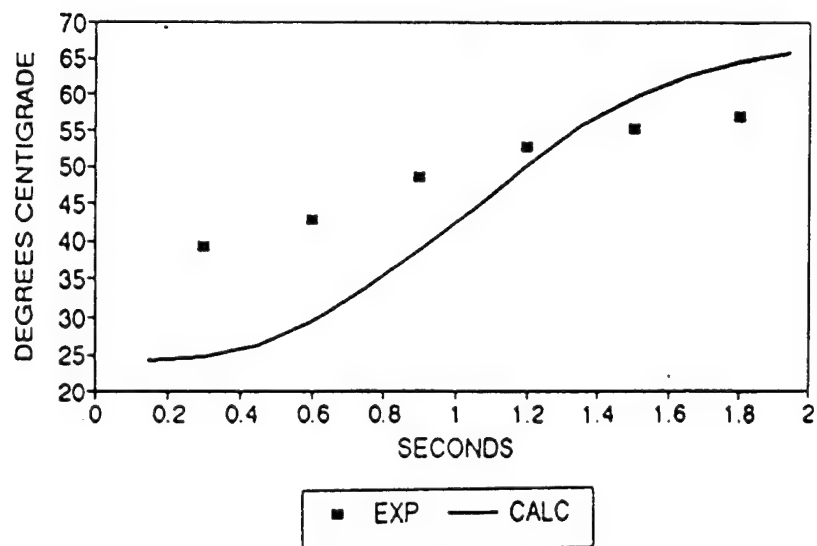


Figure 5 (e). Simulant Protected by Nomex -  
 $15.8 \times 10^4 \text{ W/m}^2$ .

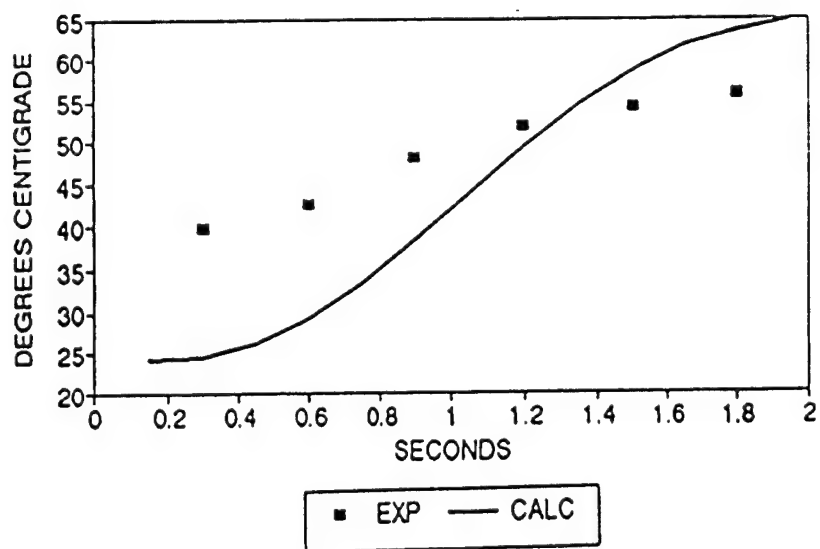


Figure 5 (f). Simulant Protected by Nomex -  
 $15.4 \times 10^4 \text{ W/m}^2$ .

## VI. THERMAL PROTECTION BY NOMEX- ONE AND TWO LAYERS

The thermal protection Nomex can provide was examined by calculating the temperatures for the skin simulant material at the thermistor depth with and without Nomex protection. The protection from heat fluxes appropriate to a flash fire ( $8.37 \times 10^4 \text{ W/m}^2$ ),  $\text{CO}_2$  laser ( $23.4 \times 10^4 \text{ W/m}^2$ ), and a nuclear explosion ( $83.72 \times 10^4 \text{ W/m}^2$ ) were evaluated. (The specific flux used for these calculations, which is appropriate for a flash fire, is also the flux which is used for the standard thermal protective performance (TPP) test.) Numerical results are provided in Tables 4(a). and 4(b). Figures 6(a). - 6(c). show the results graphically. Figure 7 shows the temperature reductions in the skin simulant that result from Nomex protection for heat fluxes from the three different sources.

The highest temperature for the unprotected simulant occurs at approximately one second. The greatest temperature reduction which results from Nomex protection also occurs at this time. For flash fire exposure, the unprotected simulant reaches a temperature of  $83^\circ\text{C}$  ( $181^\circ\text{F}$ ). Under the same conditions, the simulant protected by Nomex has a temperature of  $32^\circ\text{C}$  ( $90^\circ\text{F}$ ). Similarly, for  $\text{CO}_2$  laser exposure, the unprotected simulant can reach  $188^\circ\text{C}$  ( $370^\circ\text{F}$ ), while the protected simulant has a temperature of  $46^\circ\text{C}$  ( $115^\circ\text{F}$ ). For nuclear weapons' exposure, the unprotected simulant reaches a temperature of  $610^\circ\text{C}$  ( $1130^\circ\text{F}$ ), while the protected simulant has a temperature of  $101^\circ\text{C}$  ( $214^\circ\text{F}$ ). For these three cases, Nomex protection results in temperature reductions of  $51^\circ\text{C}$  ( $124^\circ\text{F}$ ),  $142^\circ\text{C}$  ( $288^\circ\text{F}$ ), and  $509^\circ\text{C}$  ( $948^\circ\text{F}$ ).

In addition, the results also show that the temperature of the unprotected simulant is still rising after approximately one second of exposure of laser time with two seconds of evaluation of the material irradiation response to each of these three different heat fluxes. This fact suggests that the Nomex protection causes a delay in the temperature rise of the simulant with the temperature peak occurring at a later time than for the unprotected simulant.



TABLE 4 (a). Thermal Protection by Nomex

S	DEGREES CENTIGRADE					
	FLASH FIRE		CO <sub>2</sub> Laser		NUCLEAR	
	Prot.	Unprot	Prot.	Unprot	Prot.	Unprot
0.15	24.21	41.20	24.22	71.73	24.26	194.24
0.30	24.45	52.81	24.89	104.18	26.66	310.33
0.45	25.36	61.93	27.45	129.67	35.81	401.56
0.60	27.01	69.69	32.04	151.36	52.26	479.16
0.75	29.23	76.55	38.27	170.56	74.52	547.84
0.90	31.88	82.78	45.66	187.96	100.99	610.10
1.05	34.82	82.41	53.89	186.95	130.41	606.47
1.20	37.93	72.58	62.58	159.47	161.52	508.15
1.35	40.78	67.04	70.54	143.96	190.00	452.67
1.50	42.97	63.20	76.69	133.22	211.98	414.27
1.65	44.53	60.29	81.05	125.11	227.59	385.22
1.80	45.59	57.98	84.01	118.64	238.19	362.09
1.95	46.28	56.08	85.94	113.32	245.10	343.05

TABLE 4 (b). Temperature Difference  
(Unprotected  
Minus Protected)

TIME (S )	FLASH FIRE (DEGS. CENT.)	CO <sub>2</sub> LASER (DEGS. CENT.)	NUCLEAR (DEGS. CENT.)
0.15	16.99	47.51	169.98
0.30	28.36	79.29	283.67
0.45	36.57	102.23	365.75
0.60	42.68	119.32	426.90
0.75	47.32	132.29	473.32
0.90	50.90	142.30	509.11
1.05	47.59	133.06	476.06
1.20	34.66	96.88	346.63
1.35	26.26	73.42	262.68
1.50	20.22	56.54	202.29
1.65	15.76	44.06	157.63
1.80	12.39	34.63	123.91
1.95	9.79	27.38	97.96

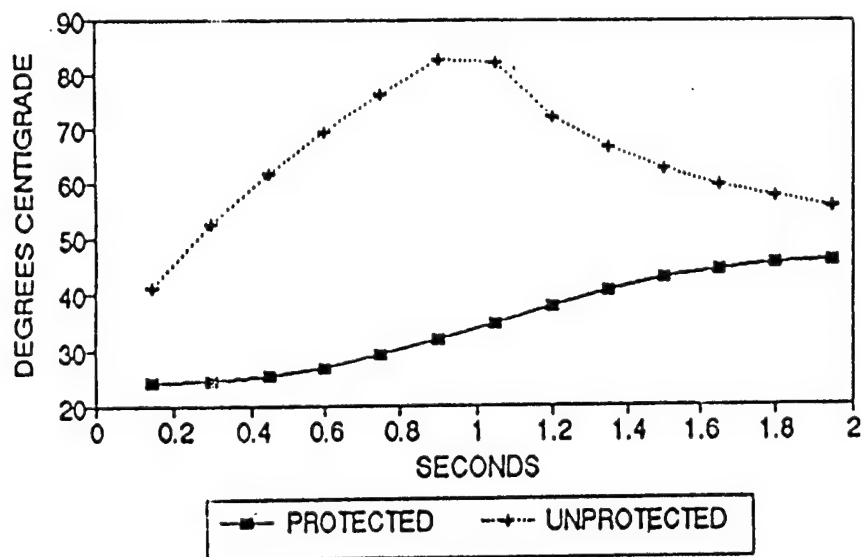


Figure 6 (a). Thermistor Depth - Flash Fire.

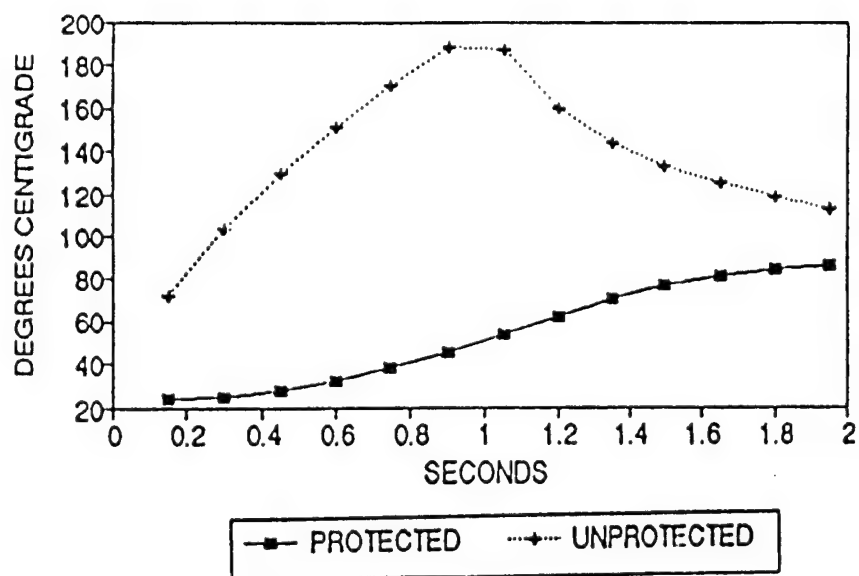


Figure 6 (b). Thermistor Depth - CO<sub>2</sub> Laser.

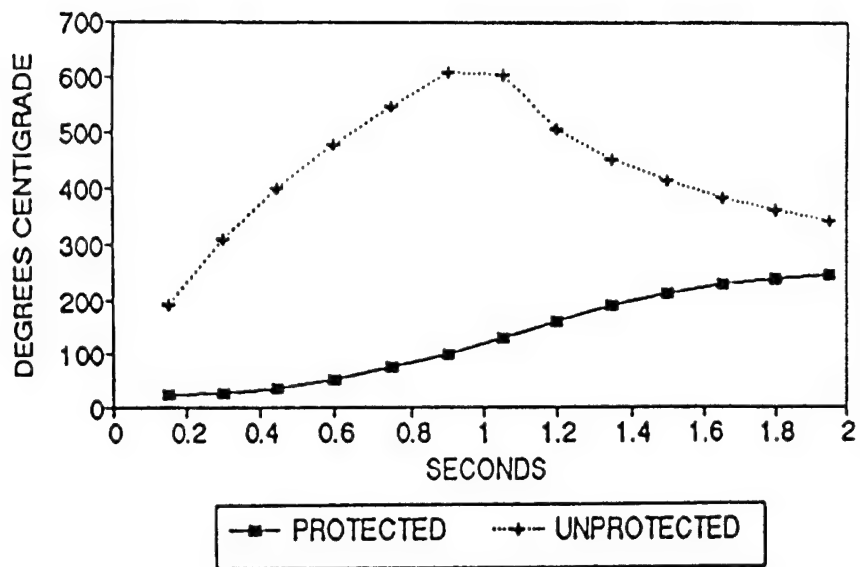


Figure 6(c). Thermistor Depth - Nuclear.

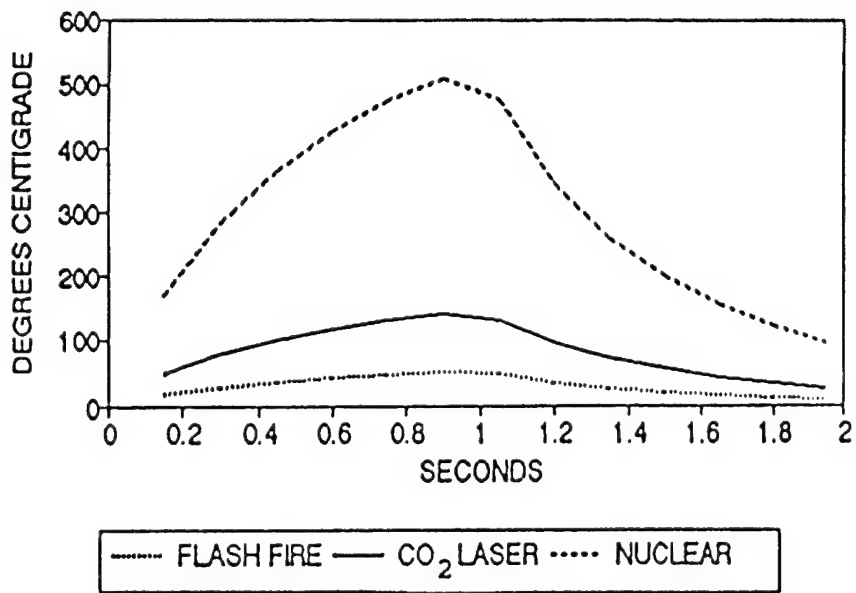


Figure 7 Nomex Protection -  
Unprotected Minus Protected.

## VII. IMPORTANCE OF MATERIAL PARAMETERS FOR NOMEX PROTECTION

The three material parameters, the density, specific heat capacity, and the thermal conductivity were evaluated for their role in the thermal protective properties of Nomex. Protection from heat fluxes appropriate to a flash fire, CO<sub>2</sub> laser and nuclear explosion were evaluated (see Section VI of this report for the numerical values of the heat fluxes). The Nomex parameters were set at plus and minus 10 percent from their values in a Nomex material (ARAMID Type 430) as specified in Du Pont's MULTIFIBER Bulletin X-272 (6) and the concomitant change in thermal protection was examined. Thus, new Nomex materials were modeled and a simulation performed by predicting their thermal protection as a function of time after irradiation. (Note: Changes of plus or minus 10 percent in the density provide the same temperature profiles as changes of plus or minus 10 percent in the heat capacity. This occurs because of the coupling of  $\rho$  and  $C_p$  as a product in the governing heat transfer equations.)

A threshold for thermal damage has been suggested to be 44°C (3). An increase in density (or heat capacity) or a decrease in thermal conductivity results in a delay in reaching this threshold and an increase in thermal protection. For example, for a flash fire, this temperature threshold has been reached at 1.65 seconds for Nomex Type 430 (Table B.1; Appendix B). Increasing the density by 10 percent delays the onset of this threshold to 1.95 seconds. Decreasing the thermal conductivity by 10 percent delays the onset of this threshold to 1.80 seconds (Table B.2). Predicted temperatures for CO<sub>2</sub> laser irradiation are provided in Tables B.3. and B.4. For nuclear weapons exposure, the calculated temperatures are provided in Tables B.5. and B.6. These results are shown graphically in Appendix Figures B.1. - B.6.

Table 5 shows the temperature reduction and the increased thermal protection which occurs for an increase of 10 percent for the density (or the heat capacity) or a decrease of 10 percent in the thermal conductivity. This table shows that the amount of increased thermal protection is a function of the time after irradiation. For the examples shown in the table, the temperature reductions first increase and then decrease within two seconds after irradiation. At the 10 percent level and during this two-second time period, there appears to be somewhat greater temperature reductions for increases in the density (or heat capacity) than for corresponding decreases in the thermal conductivity.

TABLE 5. Nomex Material Parameters' Effects on Protection: density,  $\rho$ ;  
heat capacity,  $C_p$ ; thermal conductivity,  $k$ .

S	DEGREES CENTIGRADE					
	FLASH FIRE		CO <sub>2</sub> LASER		NUCLEAR	
	$\rho$ or $C_p$ (+10%)	$k$ (-10%)	$\rho$ or $C_p$ (+10%)	$k$ (-10%)	$\rho$ or $C_p$ (+10%)	$k$ (-10%)
0.15	0.00	0.00	0.01	0.01	0.02	0.03
0.30	0.07	0.07	0.20	0.21	0.72	0.74
0.45	0.27	0.27	0.75	0.75	2.69	2.69
0.60	0.54	0.53	1.52	1.49	5.43	5.32
0.75	0.84	0.81	2.36	2.27	8.45	8.11
0.90	1.15	1.08	3.21	3.02	11.50	10.81
1.05	1.44	1.33	4.03	3.72	14.43	13.31
1.20	1.71	1.55	4.78	4.32	17.10	15.46
1.35	1.86	1.63	5.19	4.57	18.57	16.35
1.50	1.87	1.59	5.23	4.45	18.69	15.91
1.65	1.81	1.48	5.05	4.13	18.06	14.79
1.80	1.71	1.34	4.77	3.75	17.07	13.42
1.95	1.59	1.20	4.46	3.36	15.95	12.02

# **VIII. SIMULATION OF NUCLEAR PULSE USING TRAPEZOIDAL PULSE - TWO LAYERS**

Trapezoidal laser pulses can be generated in the laboratory and if their parameters (plateau times and fluxes) are appropriately adjusted, then they can be used to approximate the effect of a specified nuclear pulse. The thermal code was used in order to predict the values of these parameters so that correlations can be made between nine specified nuclear pulses (Table 6) and trapezoidal pulses. Information required to calculate temperature profiles for the nuclear pulses (Figures 8(a) - 8(c). was obtained from "The Effects of Nuclear Weapons" (7).

Twenty-four trapezoidal pulses (Table 7) were considered in order to make comparisons with the nuclear pulses. These trapezoidal pulses represent a first approximation or guess as to pulses that might be appropriate to match the nuclear pulses. A significant amount of computer time was required for these calculations because of the length of the simulated run time (five seconds) and because of the considerable number of cases.

Visual comparisons of the nuclear pulses and those trapezoidal pulses that provided the closest matches are provided in Appendix Figures C.1 - C.9. For each nuclear pulse, more than one trapezoidal pulse is shown as a possible match. The plateau times and fluxes for the trapezoidal pulses are indicated in these figures. A summary of the information presented in Appendix C is provided in Table 8.

TABLE 6.      Nine Nuclear Pulses

Pulse Number	Energy <sub>2</sub> cal/cm <sup>2</sup>	Yield kt	Tmax s	Flux W/m <sup>2</sup> x 10 <sup>4</sup>
1	10	30	0.1862	18.7344
2	10	100	0.3163	11.0286
3	10	300	0.5129	6.8010
4	20	30	0.1862	37.4685
5	20	100	0.3163	22.0573
6	20	300	0.5129	13.6024
7	30	30	0.1862	56.2029
8	30	100	0.3163	33.0857
9	30	300	0.5129	20.4034

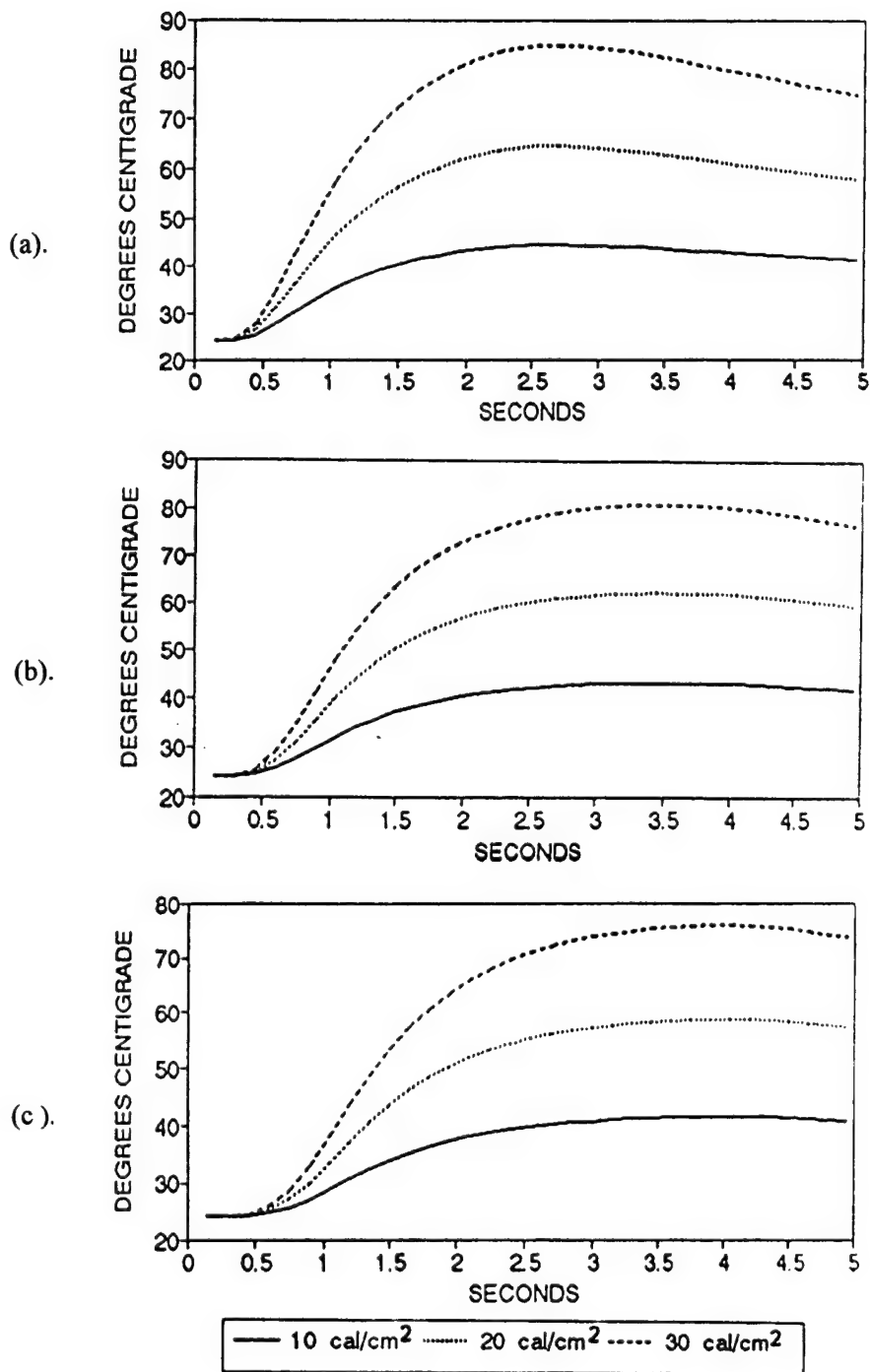


Figure 8 . Calculated Responses to Nuclear Pulses

- (a). 30 kt  
 (b). 100 kt  
 (c). 300 kt



TABLE 7. Twenty-Four Trapezoidal Pulses

Pulse Number	Plateau Time s	Flux W/m <sup>2</sup> x 10 <sup>4</sup>	Pulse Number	Plateau Time s	Flux W/m <sup>2</sup> x 10 <sup>4</sup>
1	2.0	10.0	13	1.0	18.0
2	2.0	15.0	14	1.0	15.0
3	2.0	12.0	15	1.0	12.0
4	2.0	9.0	16	1.0	9.0
5	2.0	6.0	17	1.0	6.0
6	2.0	3.0	18	1.0	3.0
7	1.5	18.0	19	0.5	18.0
8	1.5	15.0	20	0.5	15.0
9	1.5	12.0	21	0.5	12.0
10	1.5	9.0	22	0.5	9.0
11	1.5	6.0	23	0.5	6.0
12	1.5	3.0	24	0.5	3.0

TABLE 8. Correlations between Nuclear and Trapezoidal Pulses

#	NUCLEAR		TRAPEZOIDAL	
	Energy cal/cm <sup>2</sup>	Yield kt	Plateau s	Flux W/m <sup>2</sup> x 10 <sup>4</sup>
1	10	30	0.5	12.0
	10	30	1.0	6.0
2	10	100	1.0	6.0
	10	100	1.5	3.0
3	10	300	1.0	6.0
	10	300	2.0	3.0
	10	300	1.5	3.0
4	20	30	1.0	15.0
	20	30	1.0	12.0
	20	30	1.5	9.0
5	20	100	1.0	12.0
	20	100	1.5	9.0
6	20	300	1.5	9.0
	20	300	2.0	6.0
	20	300	1.5	6.0
7	30	30	1.5	15.0
	30	30	2.0	12.0
	30	30	1.5	12.0
8	30	100	1.0	18.0
	30	100	1.5	12.0
9	30	300	1.0	18.0
	30	300	1.5	12.0
	30	300	2.0	9.0



## IX. DISCUSSION/SUMMARY

This work uses mathematical modeling to examine the topic of individual thermal protection afforded by a clothing material. Results are obtained using a thermal computer model which is being developed at NRDEC and Northeastern University. Some comparisons have been made between calculated and experimental results. These comparisons are reasonable considering the approximations made for input parameters and experimental variations. The thermal protection which Nomex affords from a flash fire, CO<sub>2</sub> laser irradiation, and a nuclear weapon are predicted; temperatures at the epidermis/dermis interface (basal epidermal layer) for skin simulant are calculated. Nomex protection delays the temperature rise of skin simulant. Simulations are performed examining the protective effects of new materials which have material parameters altered from their Nomex values for different heat fluxes. Increasing the density (or heat capacity) or decreasing the thermal conductivity results in additional delays in the temperature rise of protected skin simulant. Finally, a correlation is achieved between specified nuclear pulses and trapezoidal pulses to facilitate work concerning nuclear weapons.

Determining values for material parameters (or reasonable approximations) for input to the computer code can be difficult as was illustrated when obtaining approximations for  $\rho$ ,  $C_p$ , and  $k$  for both of the materials evaluated here (skin simulant and Nomex). Values for the material parameters were restricted to be constants throughout the entire material over the time for which temperature predictions were calculated. Also, it was assumed that the values of  $\rho$ ,  $C_p$ , and  $k$  for Nomex were appropriate for the entire Nomex volume without taking into account the air volume in the material.

Calibrating the code to a specific material can be time consuming. For example, the minimum number of nodes required to make temperature predictions needs to be determined by several sequential calculations. Since the flux within an irradiated material is a function of depth from the irradiated surface, it is important to perform calculations at the appropriate depth for these calibrations (the back surface for single layer Nomex and the thermistor location for single layer simulant or two layer simulant/Nomex calculations).

Calculations reported here were limited to two seconds after laser irradiation (five seconds for nuclear pulses).

Circulatory effects are not included in the thermal model and therefore the heat dissipating effects of blood circulation are not included. Knox (8) found that this was not a factor for exposures less than 16 seconds.

The reason for choosing the epidermis/dermis simulant depth for temperature predictions is that there has been a correlation in the literature between temperatures at this depth and skin burn; this correlation is not made in this present work. Future work could use the temperatures provided in this report to predict skin burn for thermal conditions examined here.

Future work could extend the correlation of trapezoidal and nuclear pulses by examining additional trapezoidal pulses so that better correlations can be achieved with the nuclear pulses. This aspect of this work provides an excellent illustration of one way in which computer modeling can not only save laboratory time and effort but can also work hand-in-hand with experimental efforts in order to achieve valuable information to improve individual protection.

## **X. REFERENCES**

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5. Derksen, Willard L., Delhery, Guy P., Monohan, Thomas, I., and McGreevy, J. M., "Thermal and Optical Properties of the NML Skin Simulant", Naval Material Laboratory, Final Report, January 1960.
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7. "The Effects of Nuclear Weapons", DA Pamphlet No. 50-3, March 1977.
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## APPENDICES





## APPENDIX A - PREPROCESSOR AND POSTPROCESSOR FILES

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## Appendix A.1. Preprocessor File

ONE—  
LAYER

```
'line 1 ',0,0
'line 2 ',0.001
'line 3 ',1
'line 4 ',1
'line 5 ',1820.0,1507.0,0.5484,0.0,95000.0,0.0
'line 6 ',.002,.01,.01
'line 7 ',60,1,1
'line 8 ',0.00097,0.0
'line 9 ',0.0
'line 10 ',1,0.0
'line 11 ',1000.0
'line 12 ',2.0,1
'line 13 ',2.0,0.15
'line 14 ',.15
'line 15 ',4,3
'line 16 ',1,1
'line 17 ',1,1
'line 18 ',0.0,0.0,0.0
'line 19 ',1.e-03
'line 20 ',0.005
'line 21 ',0
'line 22 ',1,0.0,8.37E04
'line 23 ',1
'line 24 ',0
'line 25 ',0.0,0.0,0.0
'line 26 ',0.0,0.0,0.01,0.01
'line 27 ',1,1,1
'line 28 ',8.37E04
'line 29 ',1.0,0.0,0.0,0.0
'line 30 ',0.5,0.5
'line 31 ',0.00025
'line 32 ',0.0,6.28,0.0
'line 33 ',0.0,0.0,0.0
'line 34 ',0.0,0.0,0.0
'line 35 ',0.0,0.0,0.0
'line 36 ',1
'line 37 ',0.5
'line 38 ',24.2,1.0
'line 39 ',24.2
```

TWO—  
LAYER

```
'line 1 ',0,0
'line 2 ',0.001
'line 3 ',1
'line 4 ',2
'line 5 ',1820.0,1507.0,0.5484,0.0,95000.0,0.0
'line 6 ',.002,.01,.01
'line 7 ',60,1,1
'line 8 ',0.00097,0.0
'line 9 ',0.0
'line 10 ',1,0.0
'line 11 ',1000.0
'line 12 ',1380.0,1214.0,0.13,0.0,95000.0,0.0
'line 13 ',.0005,.01,.01
'line 14 ',10,1,1
'line 15 ',0.00097,0.0
'line 16 ',0.0
'line 17 ',1,0.0
'line 18 ',1000.0
'line 19 ',2.0,1
'line 20 ',2.0,0.15
'line 21 ',0.15
'line 22 ',4,3
'line 23 ',1,1
'line 24 ',1,1
'line 25 ',0.0,0.0,0.0
'line 26 ',1.e-03
'line 27 ',0.005
'line 28 ',0
'line 29 ',1,0.0,8.37E04
'line 30 ',1
'line 31 ',0
'line 32 ',0.0,0.0,0.0
'line 33 ',0.0,0.0,0.01,0.01
'line 34 ',1,1,1
'line 35 ',8.37E04
'line 36 ',1.0,0.0,0.0,0.0
'line 37 ',0.5,0.5
'line 38 ',0.00025
'line 39 ',0.0,6.28,0.0
'line 40 ',0.0,0.0,0.0
'line 41 ',0.0,0.0,0.0
'line 42 ',0.0,0.0,0.0
'line 43 ',0.0,0.0,0.0
'line 44 ',1
'line 45 ',0.5
'line 46 ',24.2,1.0
'line 47 ',24.2
```

## Appendix A.2. Postprocessor File

ONE  
LAYER

```
1
1
0,0.0001,0.005,0.005
60,1,1
.002,.01,.01
100
24.2
```

TWO  
LAYER

```
1
2
0,0.0006,0.005,0.005
60,1,1
.002,.01,.01
10,1,1
.0005,.01,.01
100
24.2
```

## APPENDIX B - MATERIAL PARAMETER EFFECTS

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TABLE B.1. Density or Specific Heat  
Effect for Nomex for  
Flash Fire

S	DEGREES CENTIGRADE		
	(Type 430 -10%)	(Type 430)	(Type 430 +10%)
0.15	24.21	24.21	24.20
0.30	24.55	24.45	24.37
0.45	25.72	25.36	25.09
0.60	27.70	27.01	26.46
0.75	30.28	29.23	28.39
0.90	33.28	31.88	30.73
1.05	36.55	34.82	33.38
1.20	39.95	37.93	36.22
1.35	42.92	40.78	38.92
1.50	45.09	42.97	41.10
1.65	46.54	44.53	42.73
1.80	47.46	45.59	43.89
1.95	48.01	46.28	44.69

TABLE B.2. Thermal Conductivity  
Effect for Nomex  
for Flash Fire

S	DEGREES CENTIGRADE		
	(k is Type 430 -10%)	(k is Type 430)	(k is Type 430 +10%)
0.15	24.20	24.21	24.21
0.30	24.37	24.45	24.53
0.45	25.09	25.36	25.65
0.60	26.47	27.01	27.54
0.75	28.42	29.23	30.03
0.90	30.80	31.88	32.91
1.05	33.49	34.82	36.07
1.20	36.38	37.93	39.36
1.35	39.14	40.78	42.25
1.50	41.38	42.97	44.37
1.65	43.05	44.53	45.80
1.80	44.25	45.59	46.72
1.95	45.08	46.28	47.28

TABLE B.3. Density or Specific Heat  
Effect for Nomex  
for CO<sub>2</sub> Laser

S	DEGREES CENTIGRADE		
	(Type 430 -10%)	(Type 430)	(Type 430 +10%)
0.15	24.23	24.22	24.21
0.30	25.19	24.89	24.69
0.45	28.46	27.45	26.69
0.60	33.99	32.04	30.53
0.75	41.20	38.27	35.90
0.90	49.57	45.66	42.45
1.05	58.72	53.89	49.85
1.20	68.22	62.58	57.80
1.35	76.53	70.54	65.35
1.50	82.59	76.69	71.46
1.65	86.66	81.05	76.00
1.80	89.24	84.01	79.24
1.95	90.76	85.94	81.48

TABLE B.4. Thermal Conductivity  
Effect for Nomex  
for CO<sub>2</sub> Laser

S	DEGREES CENTIGRADE		
	(k is Type 430 -10%)	(k is Type 430)	(k is Type 430 +10%)
0.15	24.21	24.22	24.23
0.30	24.68	24.89	25.13
0.45	26.69	27.45	28.25
0.60	30.56	32.04	33.55
0.75	36.00	38.27	40.49
0.90	42.64	45.66	48.56
1.05	50.16	53.89	57.39
1.20	58.26	62.58	66.58
1.35	65.97	70.54	74.66
1.50	72.24	76.69	80.59
1.65	76.91	81.05	84.60
1.80	80.26	84.01	87.17
1.95	82.58	85.94	88.72

TABLE B.5. Density or Specific Heat  
Effect for Nomex  
for Nuclear

S	DEGREES CENTIGRADE		
	(Type 430 -10%)	(Type 430)	(Type 430 +10%)
0.15	24.30	24.26	24.24
0.30	27.73	26.66	25.94
0.45	39.43	35.81	33.13
0.60	59.22	52.26	46.84
0.75	85.03	74.52	66.07
0.90	114.98	100.99	89.50
1.05	147.70	130.41	115.97
1.20	181.69	161.52	144.42
1.35	211.43	190.00	171.43
1.50	233.12	211.98	193.29
1.65	247.66	227.59	209.53
1.80	256.89	238.19	221.12
1.95	262.34	245.10	229.14

TABLE B.6. Thermal Conductivity  
Effect for Nomex  
for Nuclear

S	DEGREES CENTIGRADE		
	(k is Type 430 -10%)	(k is Type 430)	(k is Type 430 +10%)
0.15	24.23	24.26	24.30
0.30	25.92	26.66	27.53
0.45	33.12	35.81	38.68
0.60	46.94	52.26	57.65
0.75	66.41	74.52	82.47
0.90	90.18	100.99	111.34
1.05	117.09	130.41	142.94
1.20	146.06	161.52	175.02
1.35	173.65	190.00	204.74
1.50	196.07	211.98	225.97
1.65	212.79	227.59	240.30
1.80	224.77	238.19	249.50
1.95	233.08	245.10	255.03

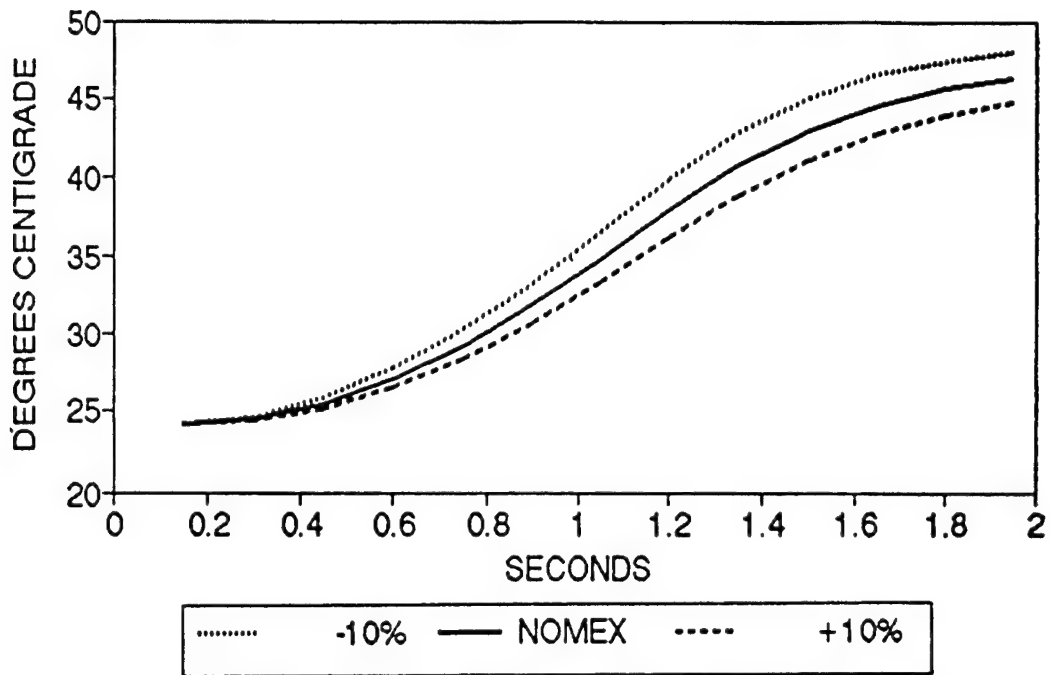


Figure B.1. Effect of Density or Heat Capacity for Nomex for Flash Fire.

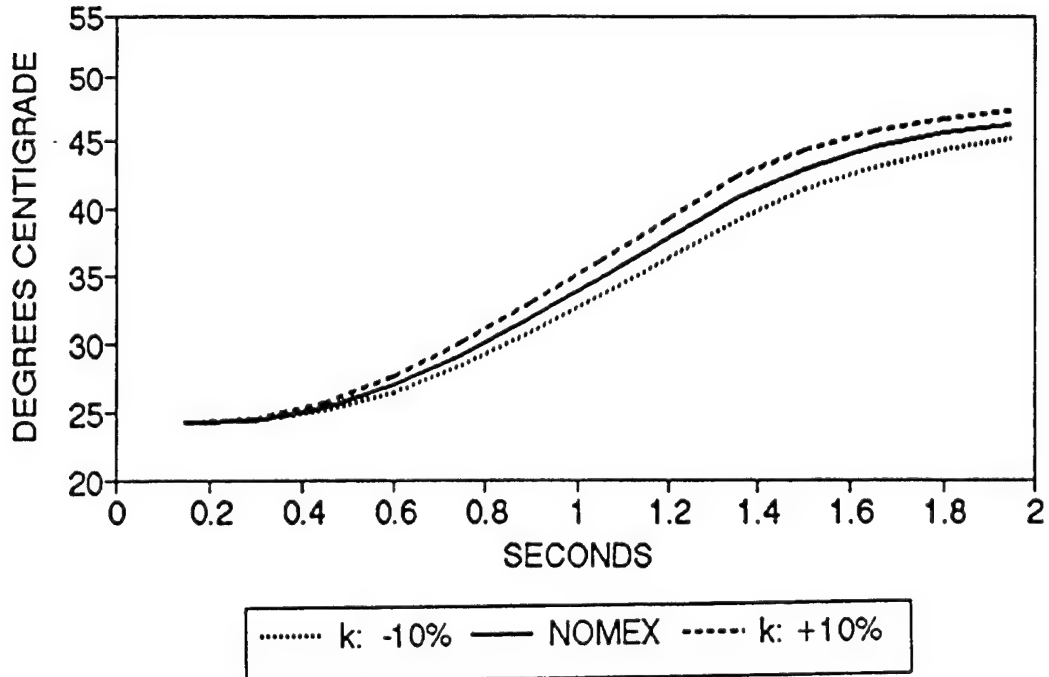


Figure B.2. Effect of Thermal Conductivity of Nomex for Flash Fire.

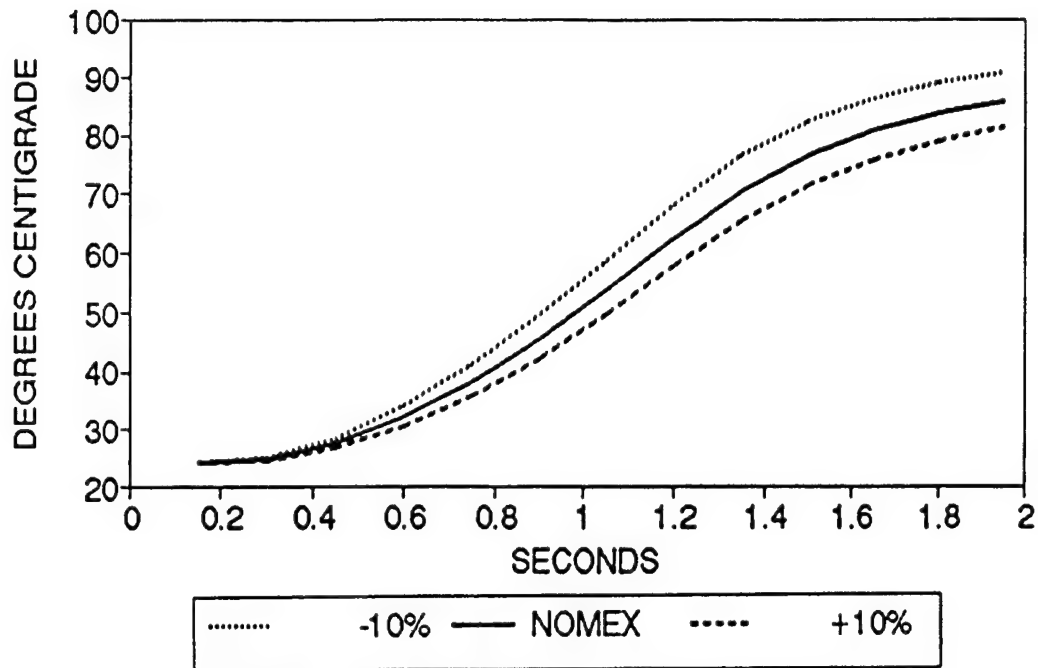


Figure B.(3). Effect of Density or Heat Capacity for Nomex for CO<sub>2</sub> Laser.

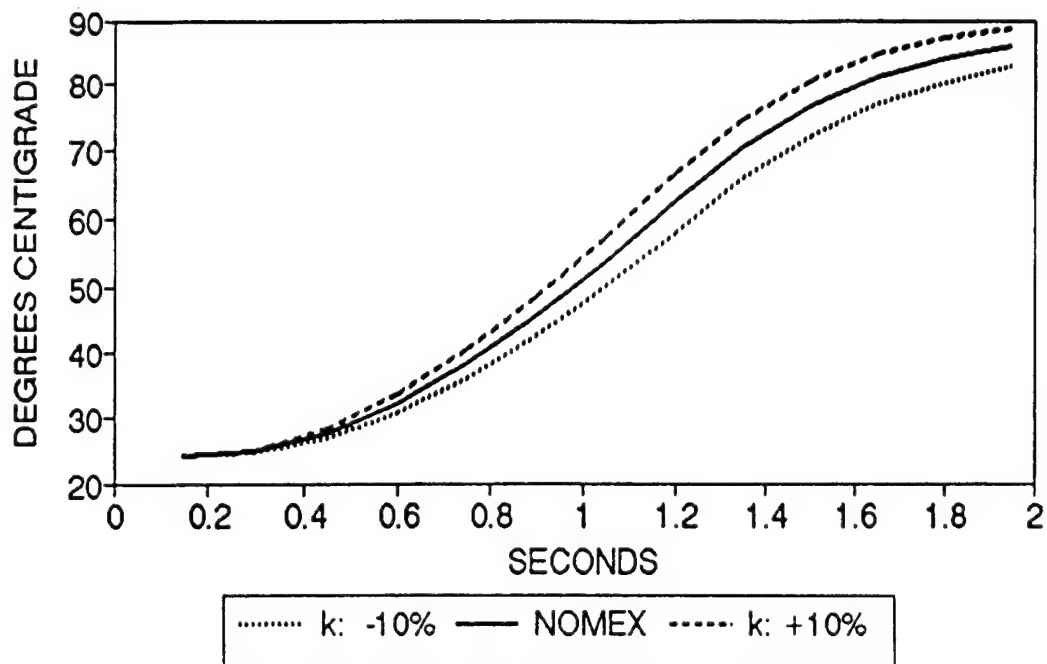


Figure B.(4). Effect of Thermal Conductivity of Nomex for CO<sub>2</sub> Laser.



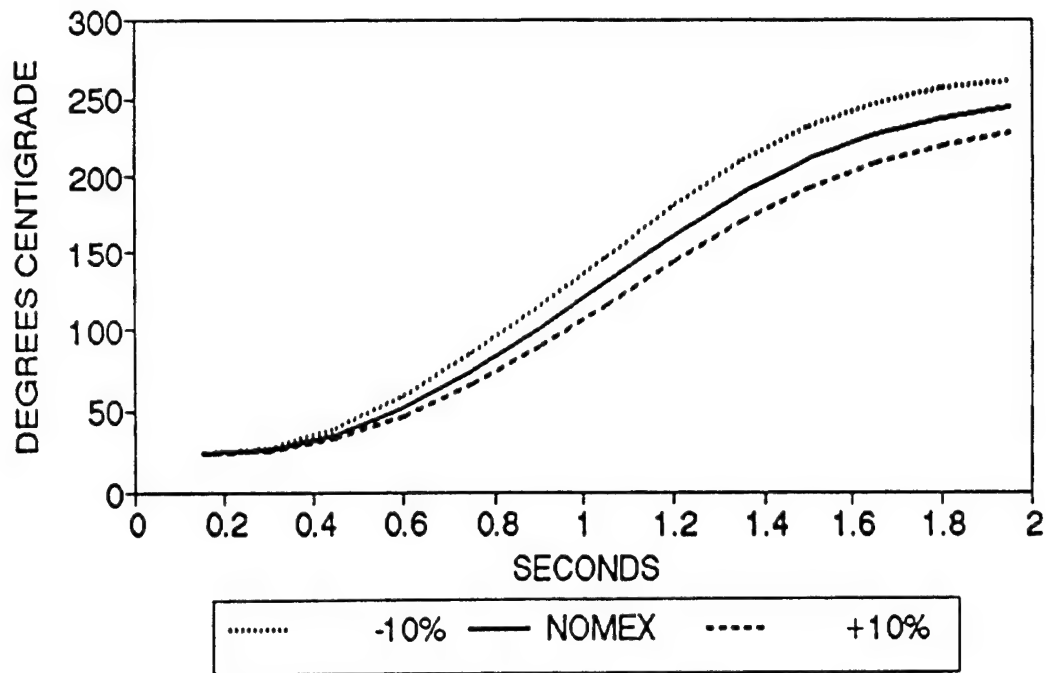


Figure B.(5). Effect of Density or Heat Capacity of Nomex for Nuclear.

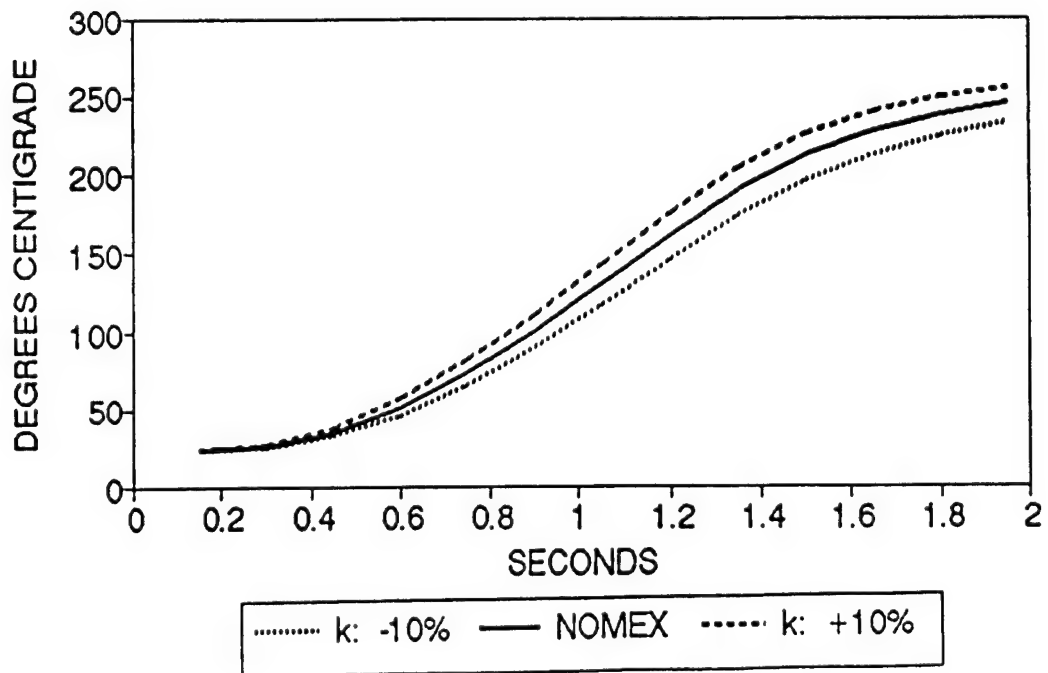


Figure B.(6). Effect of Thermal Conductivity of Nomex for Nuclear.

## APPENDIX C - TRAPEZOIDAL AND NUCLEAR PULSES

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C.9 Nuclear versus Trapezoidal -30 cal/cm <sup>2</sup> , 300 kt	54

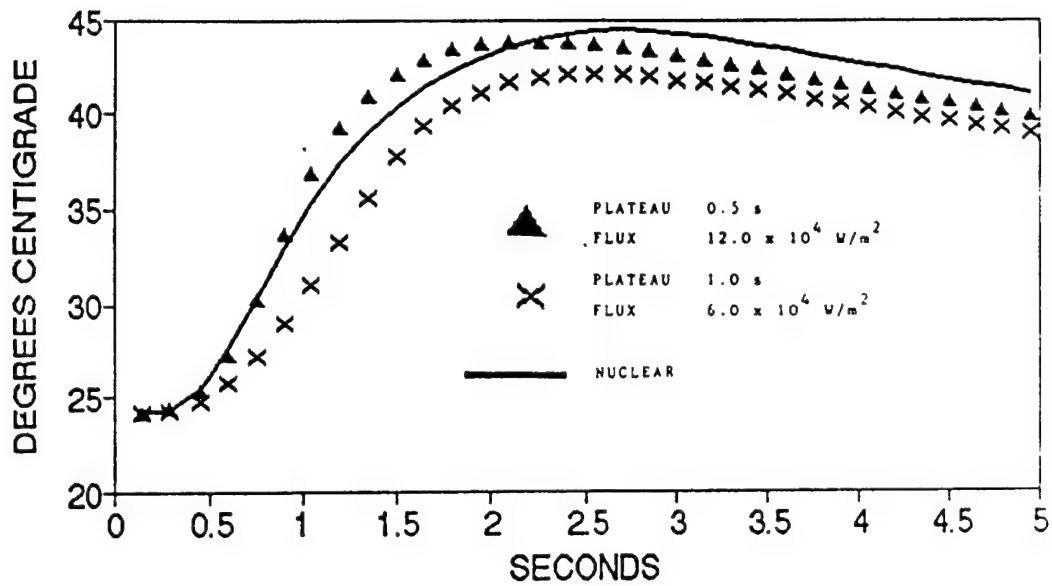


Figure C.1. Nuclear versus Trapezoidal -  $10 \text{ cal/cm}^2$ , 30 kt.

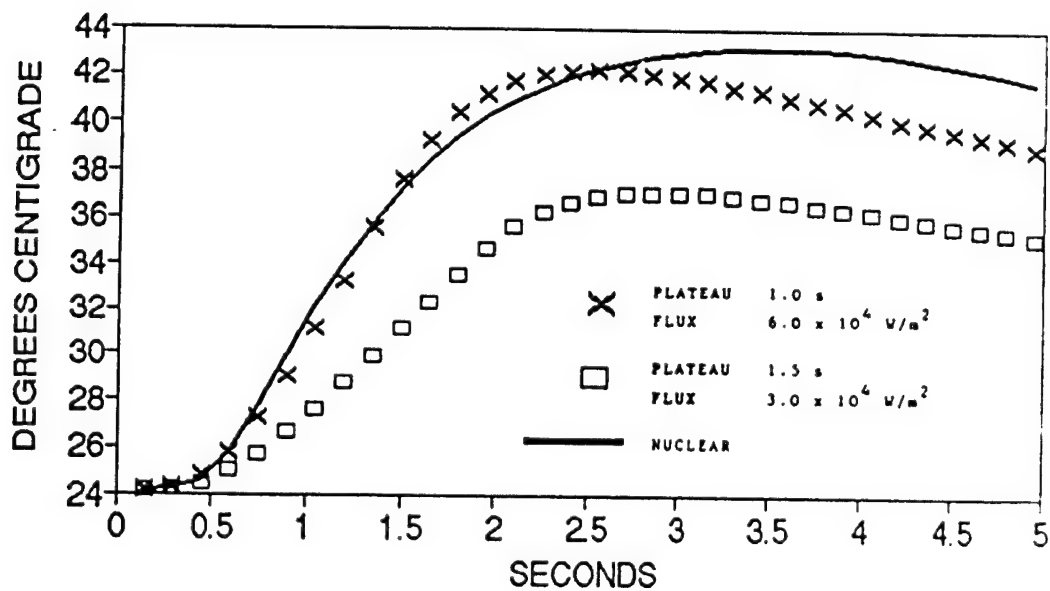


Figure C.2. Nuclear versus Trapezoidal -  $10 \text{ cal/cm}^2$ , 100 kt.

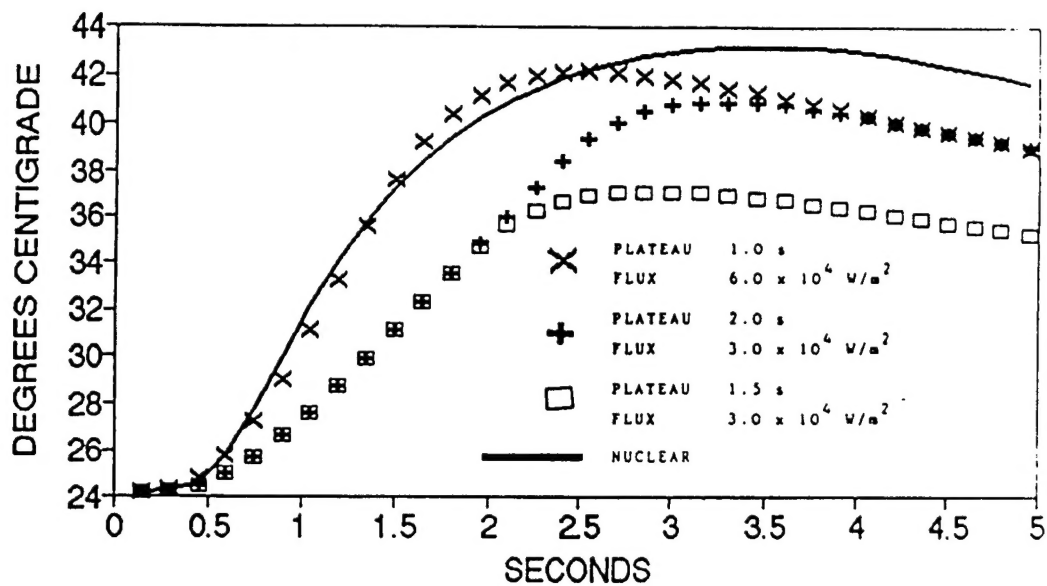


Figure C.3. Nuclear versus Trapezoidal -  $10 \text{ cal/cm}^2$ , 300kt.

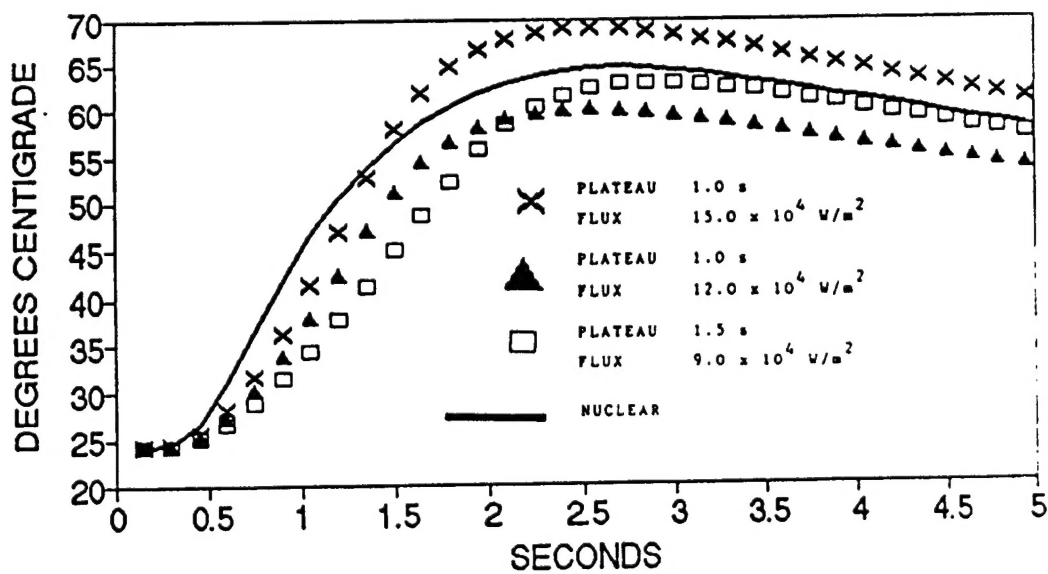


Figure C.4. Nuclear versus Trapezoidal -  $20 \text{ cal/cm}^2$ , 30 kt.

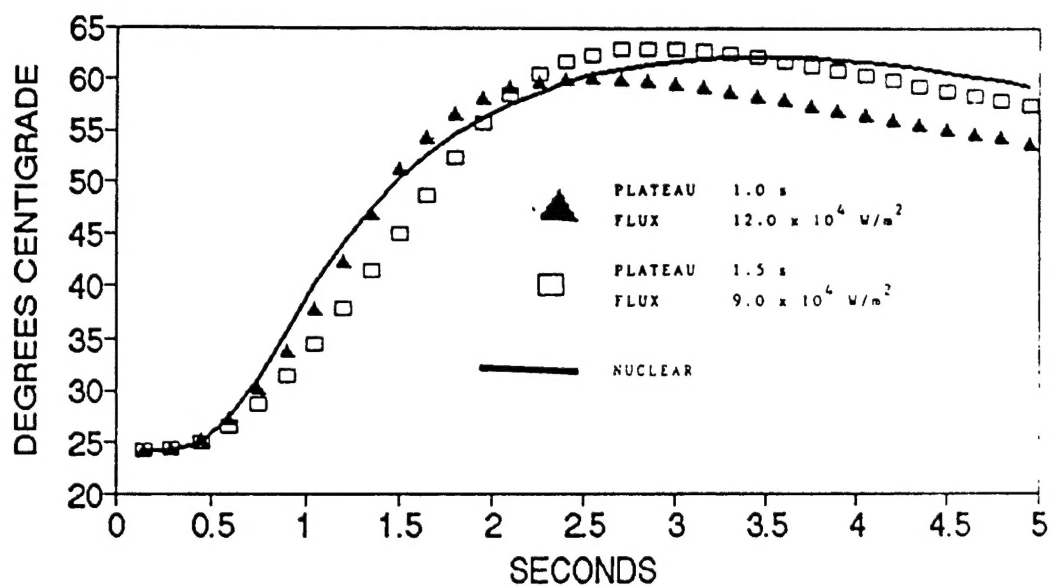


Figure C.5. Nuclear versus Trapezoidal -  $20 \text{ cal/cm}^2$ , 100 kt.

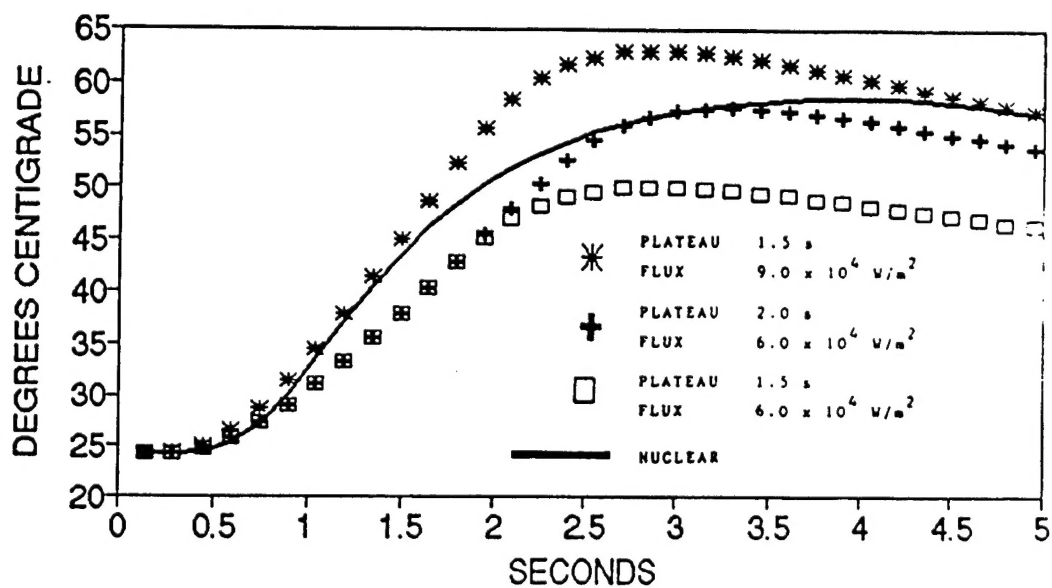


Figure C.6. Nuclear versus Trapezoidal -  $20 \text{ cal/cm}^2$ , 300 kt.

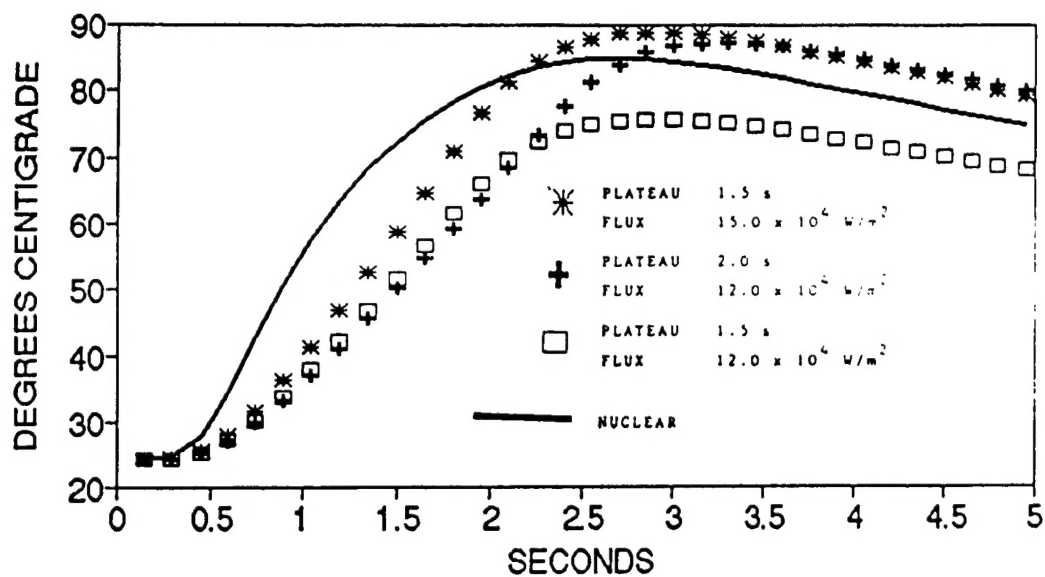


Figure C.7. Nuclear versus Trapezoidal -  $30 \text{ cal/cm}^2$ , 30 kt.

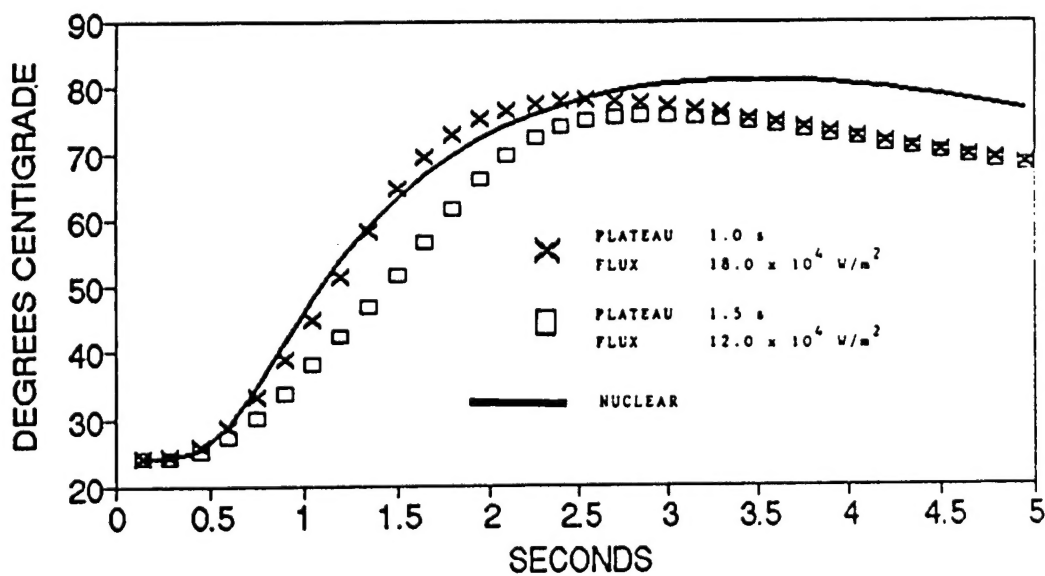


Figure C.8. Nuclear versus Trapezoidal -  $30 \text{ cal/cm}^2$ , 100 kt.

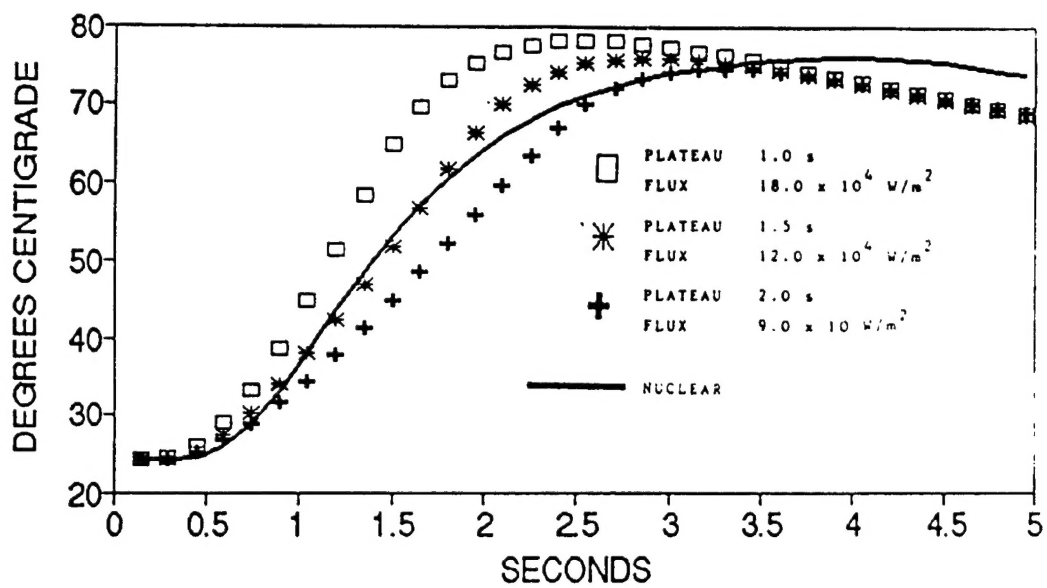


Figure C.9. Nuclear versus Trapezoidal -  $30 \text{ cal/cm}^2$ , 300 kt.